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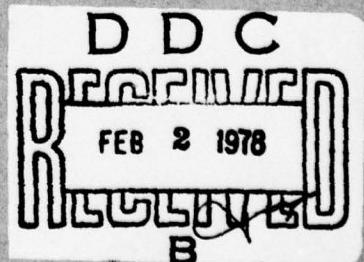November 1977

A LASER DEFECT REPAIR SYSTEM FOR SAW DEVICES

Quantronix Corporation

Approved for public release; distribution unlimited

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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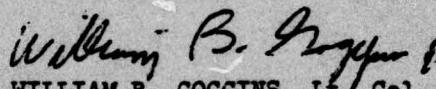
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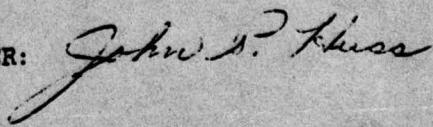
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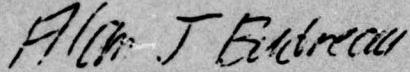
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FOR THE COMMANDER:

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A laser system has been designed and built for the repair of defects in SAW devices. The system employs a precisely-focused beam from a frequency-doubled Nd:YAG laser to machine metallic material on or near the interdigital fingers of SAW devices, thereby removing "shorted" electrodes.

(continued)

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The study and design concentrated on the ability to machine submicro meter-sized holes by melting of the metal conductors without damaging the crystalline substrate. It was found that this was best accomplished using the 0.53 micrometer radiation of a doubled-Nd:YAG laser, expanded to provide nearly-uniform illumination of a high numerical-aperture focusing objective.

Effort was also expended on optimizing the device handling, viewing and positioning system to permit accurate machining of these small areas.

The results obtained demonstrated that repairs could be successfully made without apparent damage to the SAW devices.

EVALUATION

1. This report is the Final Technical Report on the contract.
It covers research done on the removal of short circuits from
surface acoustic wave (SAW) devices by use of 1.06 μmeter and
0.53 μmeter laser radiation pulses. An instrument to perform this
removal was developed and delivered to RADC/ET.

2. SAW devices are finding increasing use in military and other
systems due to their advantages of small size and weight, low
cost and high reliability. The development of a defect repair
system, by allowing otherwise unsatisfactory SAW devices to be
salvaged, will reduce costs by increasing yields.

[signature]

ALAN J. BUDREAU
Project Engineer

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PREFACE

This Final Technical Report on "A LASER DEFECT
REPAIR SYSTEM FOR SAW DEVICES" covering the period 1 April
1976 through 30 March 1977 was prepared by QUANTRONIX CORPORATION,
Smithtown, New York under Contract No. F19628-76-C-0160 for the
Electronic Systems Division of the Air Force Systems Command, Hanscom
Air Force Base, Massachusetts.

Dr. Martin G. Cohen was the principal investigator in this
program. Dr. T. L. Tsai, and Mr. W. Lehnert have provided substantial
technical contributions; Mr. Robert A. Kaplan has provided technical and
administrative support.

The Contracting Officers representative is Mr. Dave Plata.
The Contracting Officers Technical Representative was Dr. Ken Laker and
is now   Alan Budreau.

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1.0   INTRODUCTION

The development of high-resolution photolithographic techniques and their application to surface acoustic wave (SAW) devices has led to the production of microwave filters and delay lines employing interdigital transducers with electrode dimensions of one micro meter or less. Because the probability of producing completely defect-free devices of this type is relatively low, a repair tool which functions as a remover of excess electrode material is a useful instrument.

The goal of this work was to design, develop, fabricate and test such a repair tool for SAW devices, based on the ability of a pulsed laser to machine micro meter diameter holes in thin metallic films. The laser is uniquely suited to this machining application by virtue of the ability to precisely focus its output beam and the high peak power it can generate. Quantronix has recognized the significance of these laser properties in the solution of a related problem, i.e., the removal of excess metal defects from hard-surface, integrated-circuit photomasks. (The term hard-surface indicates that the opaque mask areas are produced with metallic or metal oxide films as opposed to silver-halide photographic emulsion). Since micro meter dimension features are standard on these masks, the design and development of the Quantronix Model 801 Mask Inspection and Repair Tool (MIRT) had involved a study and solution of laser, optical and mechanical problems which were very closely related to the problems encountered in building a laser SAW device repair tool.

The ensuing program used the Quantronix Model 801 MIRT as a starting point and then concentrated on the following considerations peculiar to the repair of SAW devices:

1. Ability to machine moderately thick ($1000 - 2000\overset{\circ}{A}$) metallic film without damage to crystalline substrates.

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2. Ability to generate submicro meter diameter machined
spots.

3. Ability to hold, position and view the SAW devices
with the necessary accuracy.

This report describes the MIRT system, details the
modifications made to meet the particular requirements of SAW device
repair, presents the results of initial system testing and then concludes
with a discussion of the problems which arose and their solution in the
final system configuration.

2.0   SYSTEM DESIGN

The Laser Repair System was designed using a Quantronix
Model 801 MIRT modified as the basic hardware. This MIRT system
is described in detail in the abridged System Description Manual attached as
Appendix A. Briefly, there are four main subsystems:

1. the laser and associated optics,
2. the microscope,
3. the motion system and
4. the power supply and control electronics.

The laser is a pulse-pumped, passively Q-switched Nd:YAG
laser operating in the TEM-00 mode. In the standard system the beam is employed
to illuminate a rectangular aperture which is imaged onto the photomask by the
microscope. The microscope also permits viewing of the photomask and
fine positioning of the imaged aperture.

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The motion system consists of a two-axis stepper-motor driven table controlled by a microcomputer. Jog, index and scan controls are located on a control panel.

To optimize the system for repair of SAW devices as opposed to photomasks, a number of modifications were made to these subsystems based on analyses and experiments. In the succeeding subsections, a description of these modifications is given.

2.1 Laser & Optics

The Nd:YAG laser in the Model 801 serves to illuminate a variable rectangular aperture with 1.06 micrometer radiation. However, because the size of the imaged spot is at the resolution limit of the optical system, it was found that the aperture served no purpose and only resulted in a loss of energy. Therefore, the optical system was redesigned to expand and nearly-collimate the laser output beam with a 10X Gallilean telescope to overfill the aperture of the microscope objective lens with a uniform intensity beam. (The reason for the near-collimation will be explained later.) The telescope also served as a beam-pointing device to align the focused spot of light precisely in the field-of-view beneath the image of the eyepiece reticle.

In addition to these optical system modifications, tests were performed to indicate the tradeoff between operation at the fundamental Nd:YAG wavelength of 1.06 micrometer and the second-harmonic wavelength of 0.53. The results of these tests, presented in the next section, indicated that, although nearly identical machined spots could be obtained with either wavelength, dispersion problems occuring at 1.06 micrometers made the second harmonic radiation the preferred choice, and the laser system was modified by the inclusion of an extra-cavity lithium iodate second harmonic generator.

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2.2   Microscope

For a lens of given numerical aperture (N.A. = η) illuminated with a coherent wavefront of constant amplitude and wavelength λ, the focal plane distribution is the well-known Airy pattern,

$$I(r) \sim \frac{J_1^2(\frac{2\pi}{\lambda}\eta r)}{(\frac{2\pi}{\lambda}\eta r)^2}$$

The first zero of this function occurs at the first zero

of $J_1(x)$, leading to the well known result $r_o = .61\lambda/\eta$. It is more convenient to use the intensity at the e^{-2} or 13% point as a measure of the optical spot radius

$$w_o = .42\lambda/\eta$$

and this will be employed herein.

This is the smallest optical spot radius achievable for a given wavelength and numerical aperture.

To achieve a smaller spot radius than that available in the Model 801, a new microscope objective was selected with N.A. = .95. (The theoretical spot radius is, therefore, about 1/2 micrometer for 1.06 micrometer radiation). In addition to a larger aperture, this objective was designed for 100X magnification, providing a total system magnification of 1000X. This larger magnification was a welcome advantage in viewing one micron wide interdigital electrode fingers.

2.3   Motion System

The ability to view one micro meter lines clearly also makes mechanical vibrations readily visible if their peak-to-peak magnitude is

equal to any substantial fraction of one micro meter. If these vibrations are rapid enough, they have the effect of blurring the image and preventing fine focussing. Unfortunately, such blurring was observed and traced to vibrations induced by a power-supply cooling fan in the X-Y table which held the SAW devices. Initial efforts attempted to eliminate this problem by isolation of the fan; however, lack of space prevented achieving a successful solution. The final design employed shock mounts to float the entire power supply and resulted in no observable vibration.

Other mechanical changes included the removal of the lower illuminator (since no light can be transmitted through the stainless steel backing plates to which the sample substrates are bonded), replacement of the cut-out mask slide with a solid slide, especially-designed to accept the SAW devices, and removal from the Model 801 of the Data Read/ Write Subunit since repair would follow immediately upon observation of a defect, obviating the need to store defect locations.

3.0   EXPERIMENTAL RESULTS WITH 1.06 MICROMETER
           RADIATION

3.1   Laser Power Adjustments

The machining of thin metallic films on a dielectric substrate by laser irradiation is accomplished by (1) focusing short pulses of laser energy onto the film (2) absorption of energy by the metal film. (3) subsequent melting and/or evaporation of the film in the heated spot to create a hole and, (4) dissipation of any excess heat, primarily via conduction through the substrate. Since step (3) above

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cannot occur unless the film is heated to a temperature in excess of its melting temperature and perhaps even to its evaporation temperature, no machining occurs until sufficient energy is absorbed; i.e., the machining threshold must be reached. In addition, if too much energy is deposited on the surface, then the excess in step (4) may be sufficient to heat the dielectric substrate to a temperature which will produce cracking, melting, or some other form of damage. Thus, it is important to irradiate the film with only the appropriate amount of energy.

To begin, measurements of laser power at the microscope stage were made by allowing the nearly-collimated laser beam to exit through an unused opening in the microscope objective turret. An Eppley calibrated thermopile detector was positioned to receive the beam and was read using a Keithley microvoltmeter. The laser was pulsed rapidly enough (1-3 Hz) to produce a steady-stage output voltage and thereby a laser power reading. Division of this power by the pulse repetition rate yielded the energy per pulse. (Note that all subsequent energy values given in this report were measured in this way). Since the unattenuated 1.06 micrometer laser output was in the range of 100μJ per pulse, the neutral-density, linear wedge attenuator was set in the beam in approximate position for an optical density of 2.0. The microscope turret was then rotated to bring the 100X objective into the beam. A SAW sample was placed on the stage and brought into focus and machining began.

3.2   Focusing

The production of holes, one micro meter in diameter requires precise control of the peak intensity of the laser pulse and also precise focusing of the beam. While the former is readily obtained by moving a linear optical density wedge across the beam as it exits from the laser, the focusing requires more care. To allow repetitive measurements, the

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visual focus of the microscope was always used as a reference. Laser
focusing was accomplished by motion of the negative lens in the Gallilean
telescope. Optimum focus was determined by machining a series of
spots with intensity near (just above) threshold and setting the lens
position at that location corresponding to the maximum spot diameter.
Note that a collimated beam at 0.53 micrometers will be focused at
the usual focal point; however, due to the variation in focal length of
the visually-achromatized microscope objective from the visible region
to 1.06 micro meters, it is necessary to slightly prefocus (nearly collimate)
the laser beam before it enters the 100X objective.

3.3   SAW Repair at 1.06μm

As mentioned above, it was possible, using the focusing
properties of the beam expansion telescope, to bring the visible field
of the SAW device and infrared beam into focus simultaneously. Machining
was performed by pulsing the laser at a given power attenuator setting
then moving the stage to a new area of film, refocusing and setting the
attenuator for a slightly different power value. This procedure was
carried out from below threshold through pulse energies that were
capable of removing a several micro meter long segment of a one micro meter wide
electrode finger.

When it became apparent from observation in the optical
microscope that holes in the vicinity of one micro meter in diameter were
being generated, a series of holes was made in the pad area where the
electrode fingers terminate. This film consisted of 200-300Å of chromium
below 700-800Å of aluminum on a lithium tantalate SAW device. The
sample was prepared for observation in a scanning electron microscope and
photographs were taken which are displayed in Figure 1. The magnification
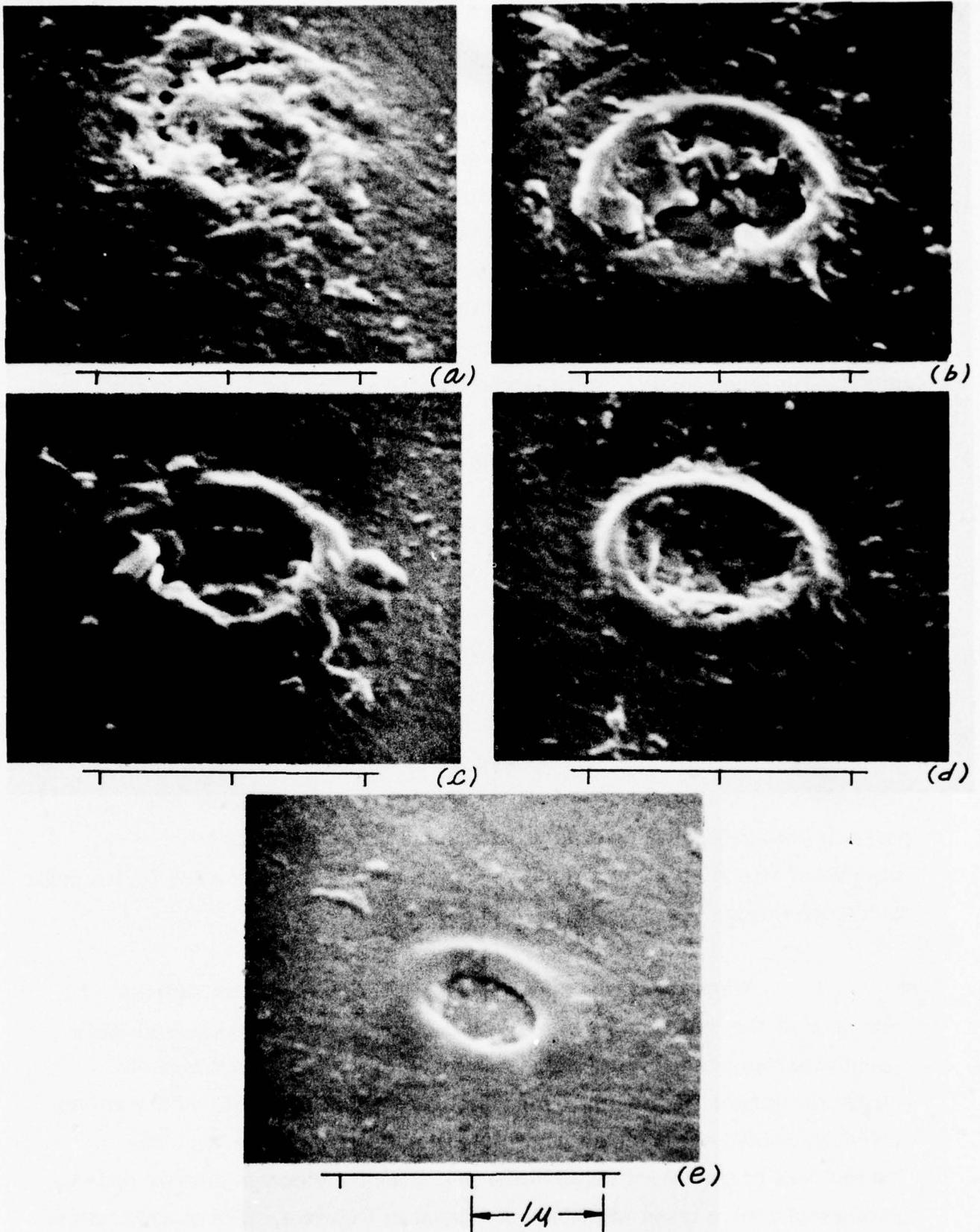
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FIG 1 SAW MACHINING AT 1.06μm

for each photo was 25,000 times; the scale at the bottom reads in micro meters.
As one progresses from (a) to (e), the various degrees of machining are
clearly evident. In (a), the film has been melted but has refused,
essentially in place but clearly lifted off the substrate. In (b), enough
energy was used to partially clear the hole. The characteristic lip,
formed by the drawing back of the molten metal due to surface tension is
apparent. Figures (c) and (d) show further progress in the clearing of
the hole which is completed in Figure 1 (e). The energy required to
produce this hole was approximately 0.5μJ.

3.4   Dispersion Effects

        While these results at 1.06 micro meters satisfied the
requirements for the generation of micron diameter holes, it was
also required that the optical system have   the ability to position the
laser beam to within 0.3 micro meters over a field. 1.0mm x 3.0 mm.
It appeared initially that the combination of a stepper-motor driven table,
with 25μm steps and a "fine-motion" system with a range of $\pm$ 25μm could
easily provide the necessary setting accuracy over the required range.
However, it was soon discovered experimentally that if a hole was generated
directly under the image of the eyepiece target reticle in the center   of
the field-of-view, then, when the fine-motion system deflected the laser beam
away from center by 25 microns, the hole generated no longer appeared
under the target reticle. "Dispersions" of 2 to 4 microns were observable,
with the visible field "leading" the hole generated by the infrared beam,
thereby preventing placement of the hole to the required accuracy.

        The cause of this effect becomes apparent if one considers
a lens with a focal length f at visible wavelengths and a longer focal
length f + Δf at 1.06μm. Imagine two beams incident on this lens as shown in

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Figure 2. The first visible wavelength beam is collimated and is incident at an angle b/f which produces a point image in the focal plane at a distance b from the central axis of the lens. Next, consider the slightly pre-focused infrared beam which also focuses in the visible focal plane at a distance f from the lens. Using the simple lens formula:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{s}$$

where p is the object distance and s the image distance, one can readily show that the infrared beam appears to come fron an object distance:

$$p = \frac{f^2}{-\Delta f}$$

Now, to calculate the position b' of the focused 1.06μm beam, note that the position off the axis of this virtual object is:

$$(L \cdot b/f + p \cdot b/f)$$

where L is the distance from beam deflector to lens as shown in Figure 2. The image position is demagnified by the image to object distances, i.e., f/p so the image position of the infrared beam is:

$$b' = f/p (L \cdot b/f + p \cdot b/f) = \frac{bL}{p} + b$$

Thus, the visible and infrared spots focus at positions differing by

$$b - b' = -\frac{bL\Delta f}{f^2}$$

This condition had been observed previously in the somewhat different optical system of the Model 801 and been corrected thereby an appropriate choice of index fluids in the "fine-motion" system. Basically,
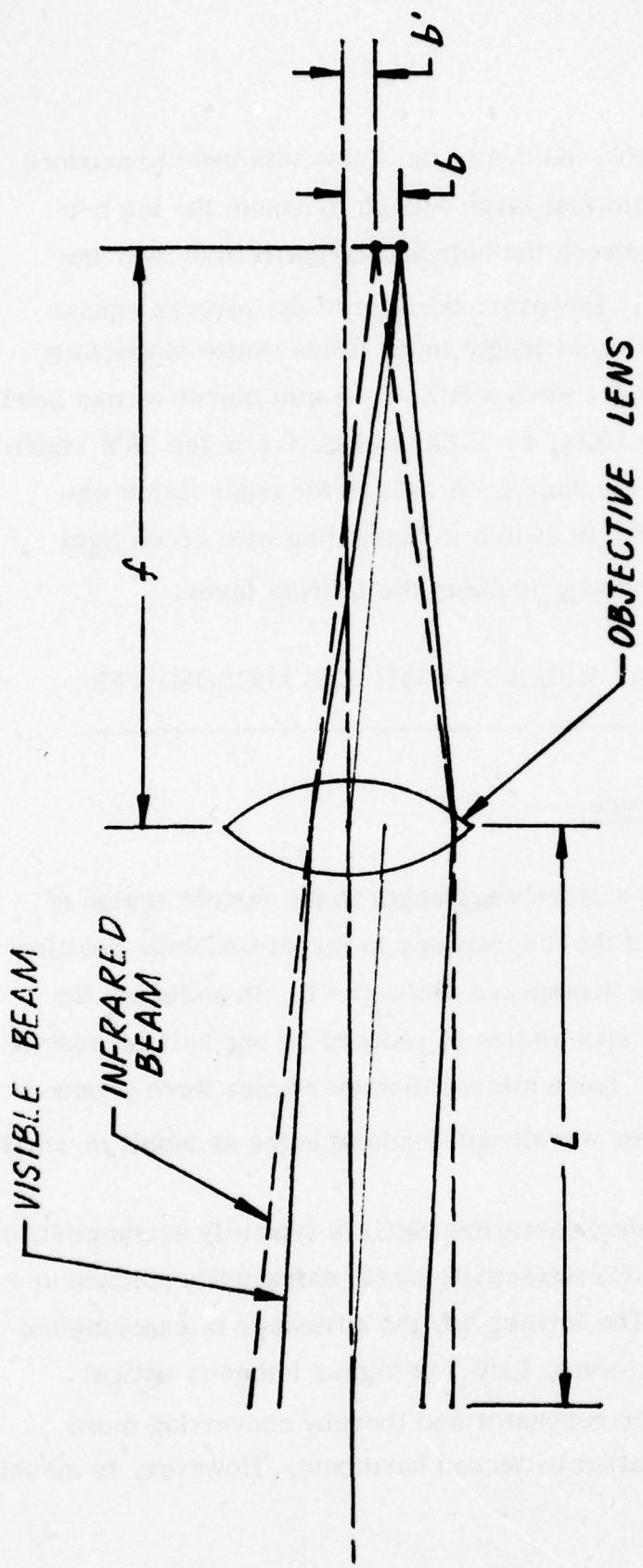
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FIG 2

VISIBLE VS. INFRARED FOCUS DIFFERENCE

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the dispersion in the refractive indices of the fluids was used to produce
a "lead" for the infrared beam just large enough to cancel the lag b-b'
resulting in good tracking between the hole and target reticle over the
$\pm 25\mu$m range of the system. However, because of the inverse square
dependence of this lag on the focal length, index fluids whose dispersion
could compensate for this effect when a 50X, f = 5 mm objective was used,
are 4 times too weak for the 100X, f = 2.5mm objective in the SAW repair
system (assuming that Δf is the same). A search for other fluids was
unsuccessful so it was decided to switch to machining with green light
at 0.53μm generated by frequency doubling the 1.06μm laser.

4.0   EXPERIMENTAL RESULTS WITH 0.53 MICROMETER RADIATION

4.1   Hardware Changes

By switching to a laser wavelength in the visible region of
the spectrum, the problem of the discrepancy in target-and-hole position
as a function of field location disappears since $\Delta f = 0$. In addition, the
theoretical minimum optical spot radius is reduced by one half because of
the reduction in wavelength. Since micron diameter holes were produced
with 1.06μm light, the shorter wavelength leads to holes as small or smaller.

Second Harmonic Generation (SHG) is typically accomplished
by either of two techniques: (1) intracavity or (2) extracavity placement
of the non-linear element. The former has the advantage of exposing the
crystal (in this case lithium iodate, $LiIO_3$) to higher intensity optical
fields within the 1.06μm laser resonator and thereby converting more
fundamental wavelength radiation to second harmonic. However, to machine

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micro meter diameter holes, so little energy is required, that the reduced complexity of method (2) was chosen.

An hermetically-sealed cell containing the SHG crystal was mounted in an assembly which allowed for both translation and angular adjustment. The assembly was placed in the optical path as shown in Figure 3. Because only a small fraction of the 1.06μm radiation is converted to green, a blocking filter was added to the optical path to completely attenuate the unused fundamental. In addition, a green-blocking, orange filter was put in the visual path above the microscope vertical illuminator to prevent any harmful level of reflected green laser light from reaching the user's eyes.

4.2   Machining Experiments

Power measurements were again made as described in Section 3.1 above and an approximate energy per pulse assigned to the scale numbers on the attenuator control dial. The graph in Figure 4 shows this calibration.

Experiments on lithium tantalate and crystal quartz substrates were carried out as before. Figure 5 shows a curve of hole diameter squared vs. pulse energy indicating the great variation in hole size achievable as the power varies above threshold.

It was again impossible to tell from optical microscope measurements alone any more than the fact that holes of less than one micron diameter were being machined. A sample was prepared for observation in the scanning electron microscope at the State University at Stony Brook but a breakdown of the SEM there prevented the taking of useful pictures.
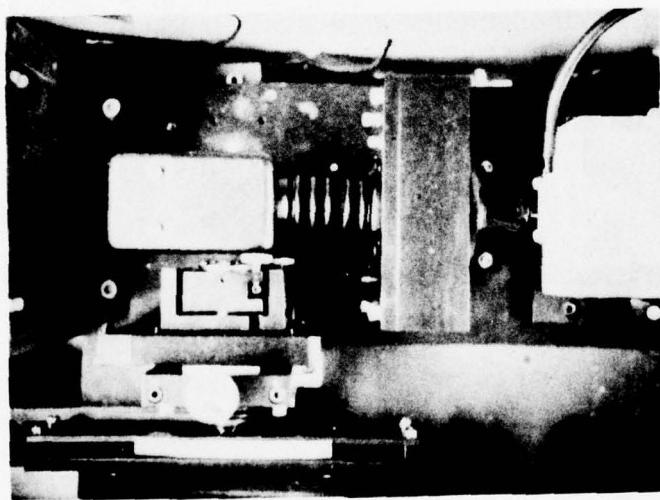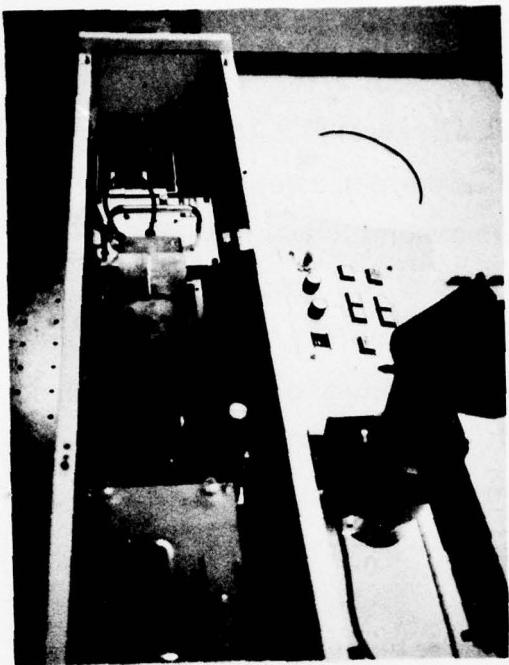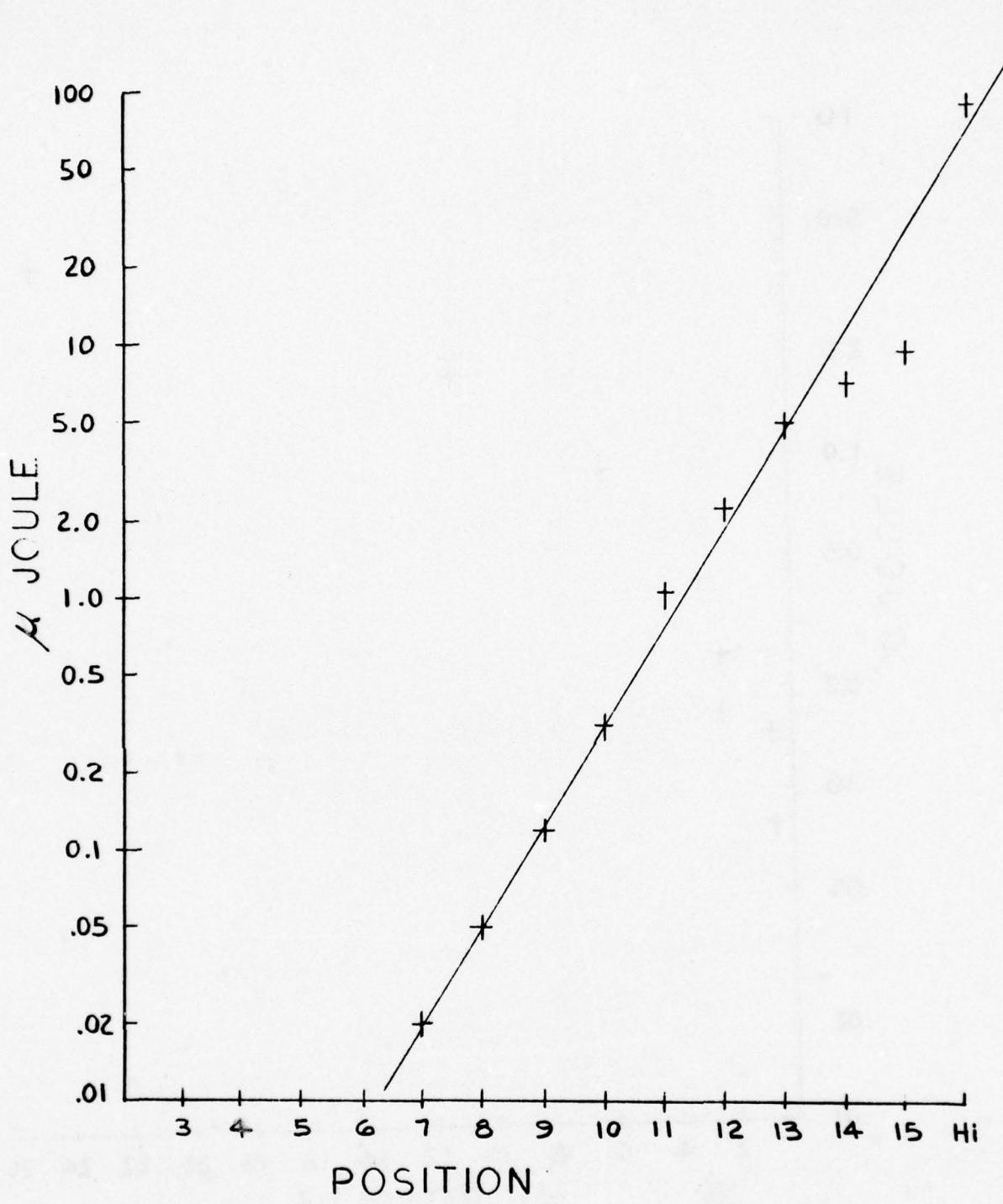
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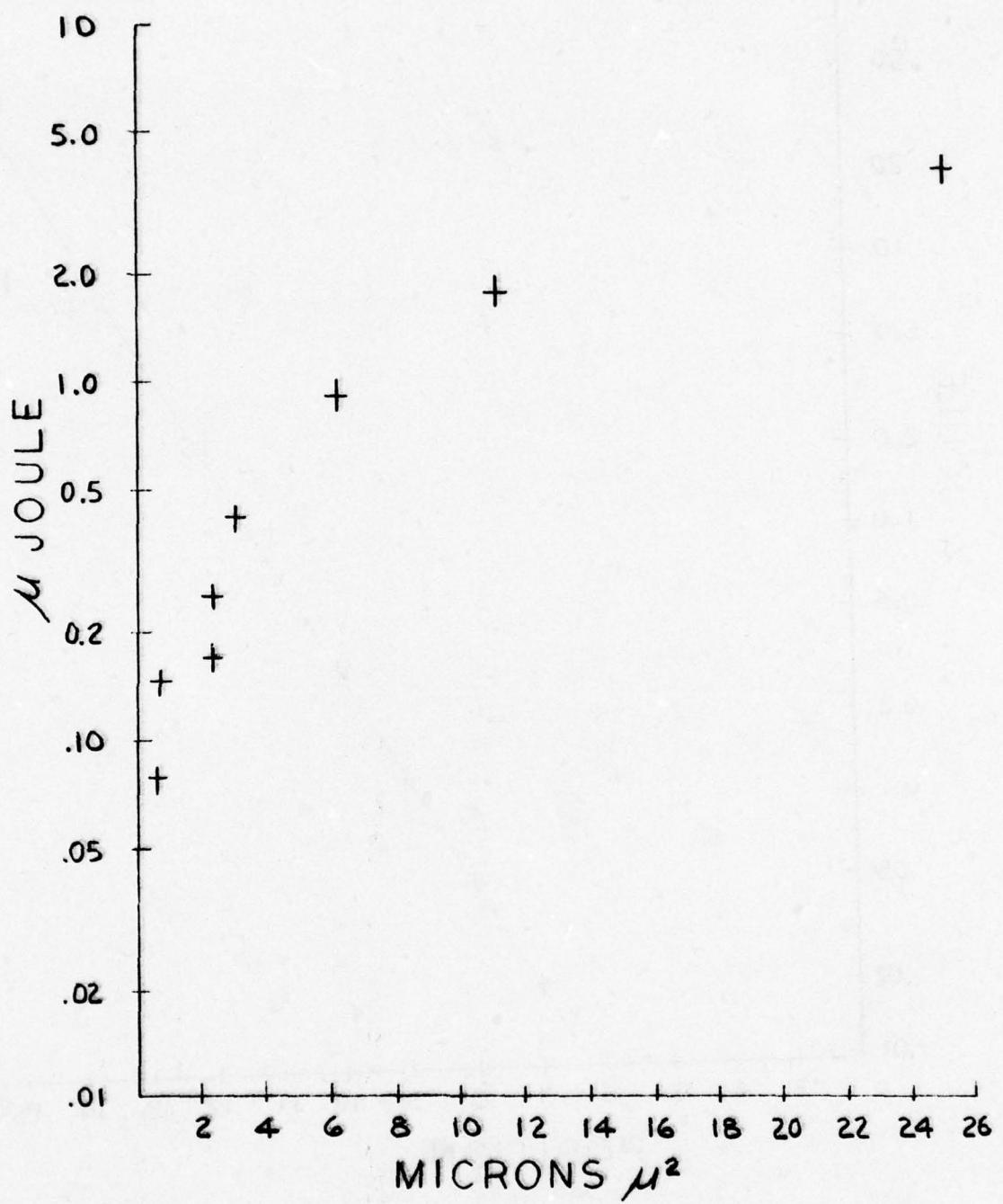FIG. 3. SHG UNIT IN OPTICAL PATH

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FIG. 4   ENERGY CONTROL CALIBRATION

FIG. 5   PULSE ENERGY VS SQUARE OF HOLE DIA.

5.0 CONCLUSIONS

The development and experiments performed during this program indicated that:

(1) it is feasible to machine submicro meter holes in thin-film SAW devices to effect repair of "shorting" defects,

(2) such machining can be accomplished without any observable substrate damage,

(3) the choice of wavelength does not depend on fundamental optical or material parameters but rather on practical considerations in the optical system design.

Ultimate performance evaluation must await experiments on active devices by the Air Force. Preliminary reports indicate that no deleterious effects are observed and that the process is a viable approach to achieving higher yields in SAW device manufacture.

APPENDIX "A"
Abridged System Manual
(Pages renumbered from original)

2116-R-4C
3050-SD-1

QUANTRONIX

MODEL 801 INSPECTION/REPAIR SYSTEM

MODEL 811 INSPECTION SYSTEM

SYSTEM DESCRIPTION

September 1976

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LASER SAFETY

Pursuant to the Radiation Control for Health and Safety Act of 1968, as amended, precautions have been taken to control laser radiation from this product. All operation, servicing and maintainence personnel are cautioned to abide by the safety instructions given in these manuals and as otherwise furnished with the product. Servicing is authorized by qualified technicians only.

DANGER

LASER RADIATION
AVOID DIRECT EXPOSURE TO BEAM
Nd: YAG   50ns
0.10J/CM² MAX
CLASS IIIb LASER PRODUCT

Laser Emission Warning Logo

HAZARDOUS POTENTIALS

Internal electronic equipment poses danger to personnel due to the presence of high voltages. Service is authorized by qualified technicians only, in accordance with the precautions given in these manuals.

DANGER
HIGH VOLTAGE

High Voltage Warning Logo

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1.0   INTRODUCTION

1.1   Background

Since its inception in the early 1960's, the Laser has
been considered as a tool for various precision micromachining
applications.   Among the various uses has been machining of thin
film materials for trimming of electronic components, such as
resistor networks, capacitors, crystal filters etc., or in the
graphic arts industry such as the Q-marc UPC Symbol Masters.
These applications generally involved machining operations on the
scale of thousandths of an inch and thus laser focusing performance
consistent with these dimensions and tolerances.   As technology
advanced, the ability to provide consistent, controllable TEM-00
mode radiation, introduced the possibility of performing these machining
operations on much smaller, micron-size features.

One application which has arisen is the use of controlled
pulses of laser radiation to repair precision photomasks and
reticles.   In this case, pulses of laser radiation are focused to
micron sized spots to remove extraneous material on hard surface
masks.   By careful control of laser energy and mode parameters,
it is possible to repair excess-material defects to submicron precision
without affecting the mask substrate.

Also required are optical, handling and logic systems consistent
with the laser performance.   This capability is now available with
the Quantronix Model 801/811 Inspection/Repair System.

A review of procedures and economics in the semiconductor
industry, a major user of precision masks and reticles, has
indicated that the ability to repair masks can offer a substantial
cost and time savings making the Model 801 System an economically
viable tool.

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1.2   Description

The Model 801 is a semiautomatic system for inspection of masks.   The Model 801 is a single unit inspection and repair system. A block diagram of this system is shown in Figure 1.3.

1.2.1   Electronics Motion Unit

The Model 801 Inspection and Repair system consists of an Electronics-Motion Unit and Laser-Optical Unit.   The Electronics-Motion contains the following subunits:

(1) A microcomputer logic subunit which performs all system calculations and interfaces with the other subunits to provide control functions.   The logic subunit comprises two replaceable P.C. cards containing (i) the microprocessor and memory and (ii) the motor drive circuits.   The cards are installed in a rack for ease of servicing.

(2) A control logic subunit comprising a P.C. board mounted on the control panel and connected by cables to two separate P.C. boards (the digiswitch board and the display board) mounted on the digi/display panel.

(3) The System Power Supply subunit which provide DC and AC power for operation of the electronic and mechanical functions of the other subunits.

(4) A two-axis stepper driven X-Y table to move and position the mask.   The table provides an absolute reference signal relative to the microscope axis ($\pm$ 1 mil) so that the absolute coordinates of all systems are coincident with each other.
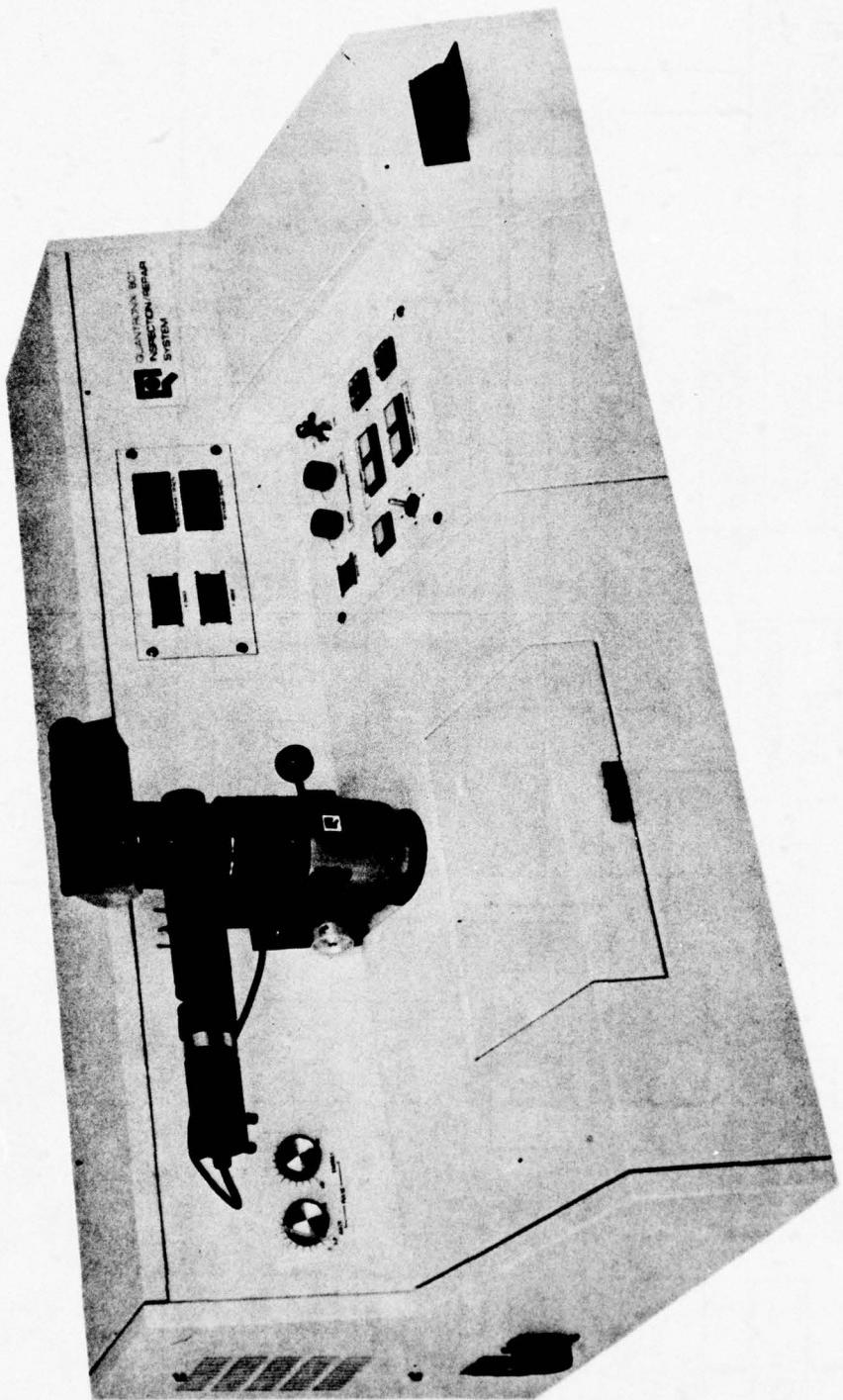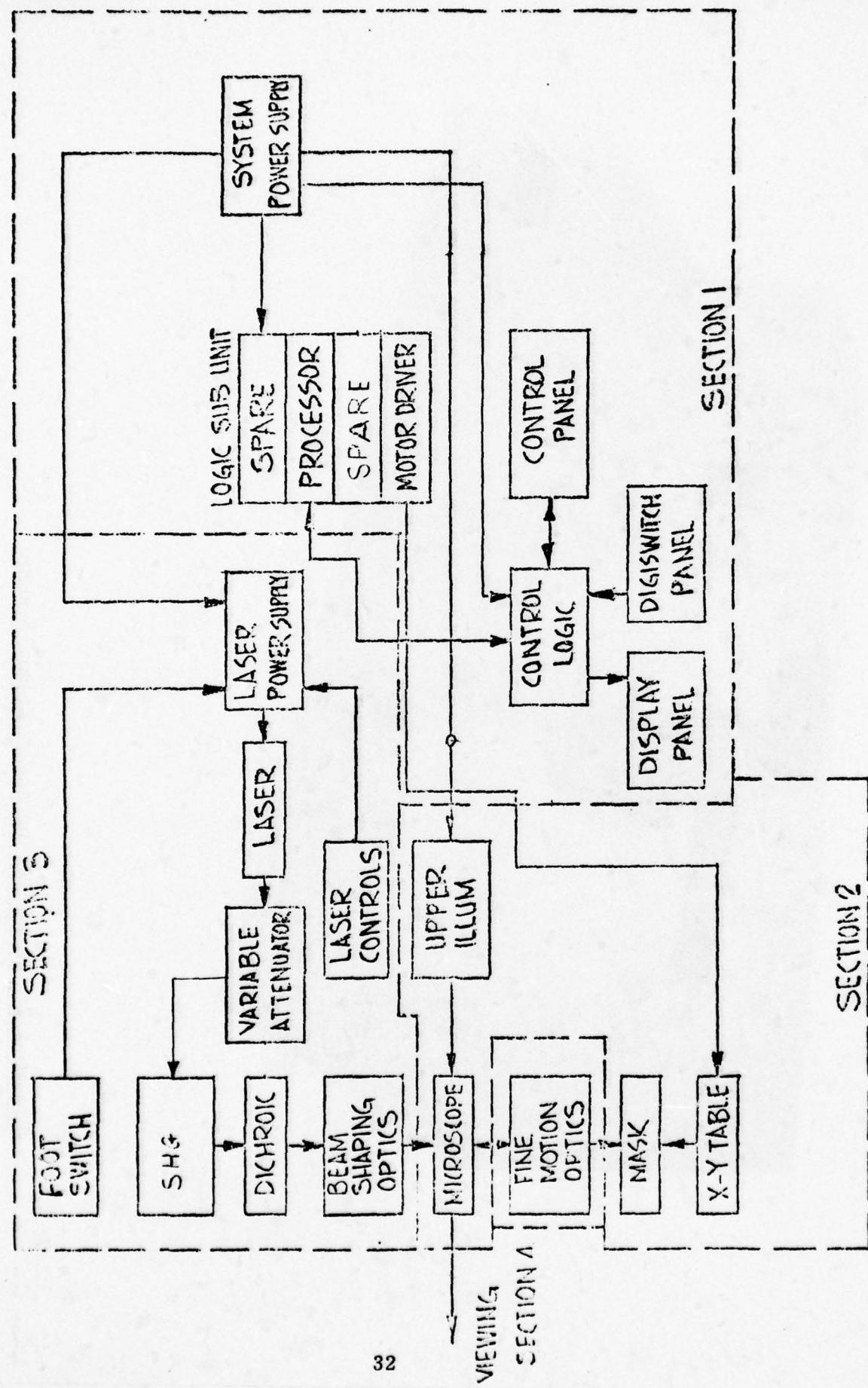
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Figure 1.2: Model 801 Inspection/Repair System

FIGURE 1.3 - BLOCK DIAGRAM OF MODEL 801 AND 811 SYSTEMS

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1.2.2 Laser-Optical Unit

The Laser-Optical unit comprises the following:

(1) A pulsed laser power supply comprising an energy storage capacitor, trigger circuit and repetition rate oscillator.

(2) An external foot switch to enable laser firing when all interlocks are properly closed.

(3) A conductively cooled, pulsed Nd:YAG laser which provides less than 100 nanosecond, 0.1 mj pulses of TEM-00 mode laser radiation at rates up to 1 pulse/second. The laser is pumped by a single FX-147C flashlamp which has a nominal life of over 10^5 pulses (equivalent to over 1 month of normal operation).

(4) A second harmonic generator (SHG) which converts the 1.06μm laser radiation to 0.53μm radiation.

(5) A variable attenuator unit to provide external control of the laser energy. Laser pumping remains constant so that other beam parameters such as mode structure beam direction and pulsewidth remain unchanged. This provides the most reliable and precise method of adjusting pulse energy for reliable removal of metallic films with minimum substrate damage on materials of various compositions or different thichnesses.

(6) A deflection dichroic to turn the beam axis 90°.

(7) Beam shaping optics which comprise an adjustable collimating telescope for optimally filling the objective lens for minimum focused spot diameters.

(8) A dichroic beam splitter to couple the laser into the microscope.

(9) Optical leverage fine motion elements to permit precise motion of the beam. The fine motion optics comprises a 2-axis differential optical wedge. The total motion of the field is $\pm$ 15 micrometers with a resolution

of 0.5 micrometers. The optical demagnification is such that a mechanical motion of 1.6 degrees (20 mil (550 μ) motion of control knob) produces a motion of only 1 micrometer of the beam.

(10) The high quality Leitz microscope is provided with binocular viewing and reflected and transmitted illumination as in the Model 801. The 2 objectives (10X, 100X) provide magnifications of 100X and 1000X with fields of view of .070 inch (1.8 mm), and .007 inch (0.2 mm) respectively.

TABLE 1.1

Sheet 1

Specifications

Microscope:	Leitz optics		
	Magnification	100X	1000X
	Field of view - Model 801 (diameter)	.070"	.007"
	Illumination: Reflected light		
	Fine motion - Model 801: $\pm 15\mu m$ with 0.5μ resolution		

Table:	Resolution:	.001 inch
	Accuracy:	+.001 inch
	Travel:	5 x 5 inches
	Flatness:	+25μ
	Speed:	Up to 0.6 ips
	Index:	1 to 999 mils, separately setable for X and Y

Laser:	Type:	Nd:YAG w/SHG
	Wavelength:	0.53μ
	Mode:	TEM-00
	Rep rate:	Single pulse to 1 pps

Table 1.1 (continued)

Sheet 2

Machining Performance (1):

Parameter	Objective Lens
	100X
Size range	0.8 - 2 microns
Positioning Accuracy (relative to reticle)	$\pm$ 1/2 Micron
Positioning Resolution	$\pm$ 1/2 Micron

1 Specifications assume uniform material characteristics.

2.0   LASER SAFETY

2.1   Introduction

Very intense light in the near-infrared, visible, and near-ultraviolet range, from whatever source, constitutes a danger to the eye. The Model 801 operates at a visible wavelength of 0.53 micrometers. The intensity levels of the Nd:YAG laser used in this equipment is such that viewing of the direct or specularly reflected beam without proper eye protection may be hazardous. Normal operation of the Model 801 with all covers in place prevents operator exposure to excessive laser emission and, therefore, no special personnel protection is required. However, servicing and maintenance of the Model 801 may require that covers be removed for alignment or adjustment by qualified technicians. In this event, the precautions required are given in the Service Manual 3050-SM-1.

The FDA LASER PRODUCT Performance Standards, authorized by the Radiation Control and Safety of 1968, pursuant to paragraph 1040, identifies the Model 801 as a Class IIIb laser product. In accordance, the following LASER EMISSION WARNING LOGO will be found affixed to the enclosure in a prominent non-removable location.

DANGER

LASER RADIATION
AVOID DIRECT EXPOSURE TO BEAM

Nd: YAG   50ns
0.18J/CM^2 MAX
CLASS IIIb LASER PRODUCT

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Other labels, as required by the FDA specification, are internally to the enclosure. Reproductions of these labels are contained in the Service Manual, 3050-SM-1, with indication of their locations.

2.2   Safety Features

2.2.1   Laser Protection

The Model 811 has been provided with safety features which preclude exposure to the direct beam or to significant levels of scattered laser light.

In its operating configuration, a normally-closed, interlock chain acts to inhibit charging of the laser power supply except when all covers and shields are in place and a normal repair sequence is underway. The Power Supply cannot charge to permit laser operation unless:

a.   The laser compartment cover is in place.

b.   The safety door is in its fully closed position.

WARNING:

THE INTERLOCKS ON THE LASER COMPARTMENT COVER AND THE SAFETY SHIELD SHOULD NEVER BE DEFEATED

3.0   SYSTEM LOGIC

3.1   Introduction

The Model 801 Mask Inspection/Repair Tool and Model 811 Mask Inspection Tool provide the operator with capability for semiautomatic inspection and repair of masks, wafers, hybrid circuits and other devices.   This section provides a brief overview of the system logic and an introduction to machine functions and controls.   In this section the position of the table is described using the coordinate system shown in Figure 3.1.

The operation of the machine can be divided into two different cycles;

    a. INDEX Cycle,
    b. READY Cycle.
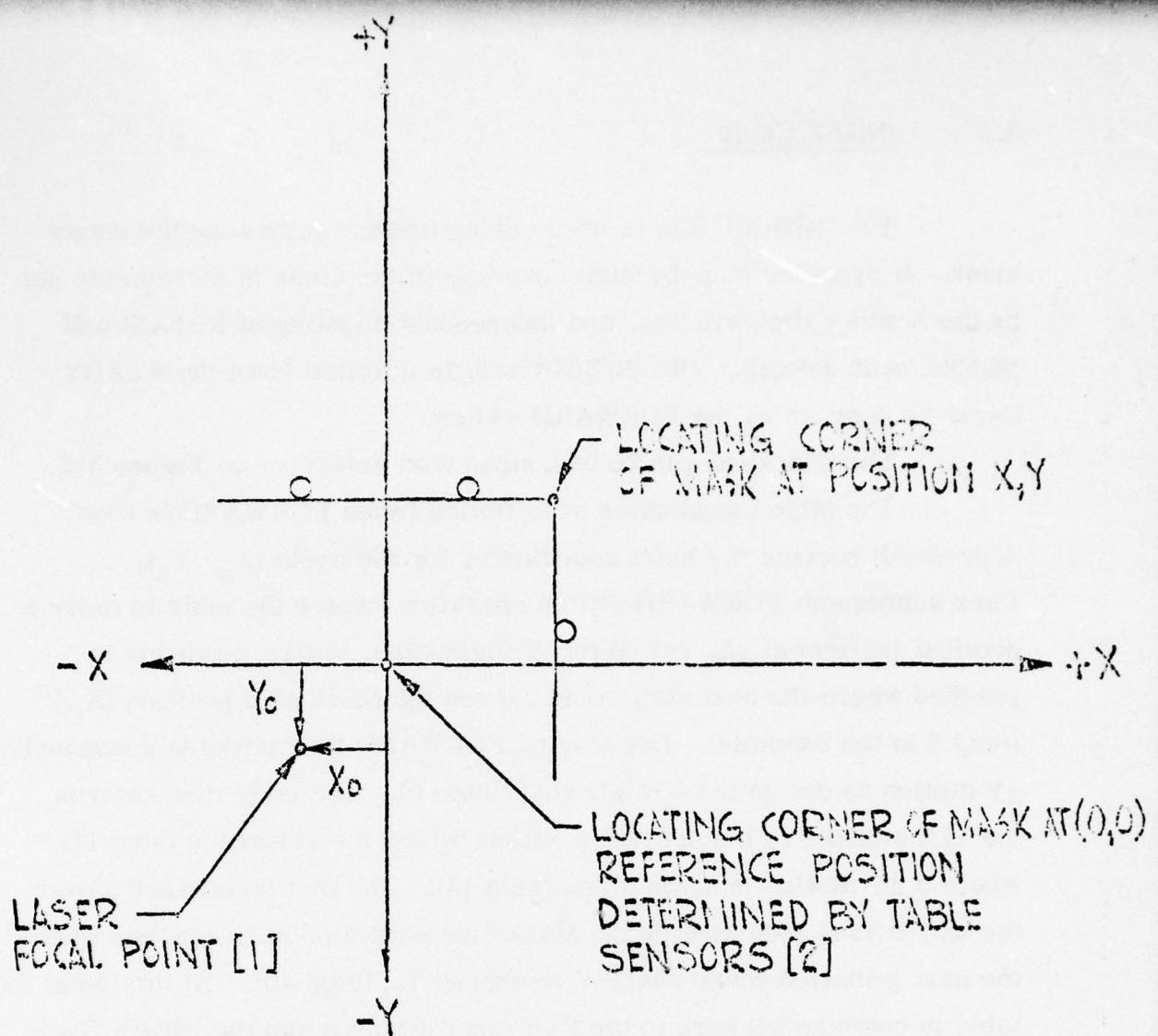
Figure 3. 1:   System Coordinates

3.2   INDEX Cycle

The INDEX Cycle is used during inspection to scan the entire mask.   It provides step-by-step coverage of the mask in increments set by the X and Y digiswitches, and independent counting of REPAIR and NONREPAIR defects.   The INDEX Cycle is initiated from the READY Cycle by depressing the FORWARD switch.

The operation can be described with reference to Figure 3-2.

The table coordinates at initiation (when FORWARD is first depressed) become the start coordinates for the cycle (X_s, Y_s). Each subsequent FORWARD switch operation causes the table to move a nominal increment ΔX, set on the X-digiswitch, until a condition is reached where the next step would exceed the mask size position (X_D) (step 5 in the example).   Depressing FORWARD then initiates a nominal ΔY motion as set on the Y-digiswitch (step 6).   The table then returns via $-\Delta X$ motions to the nearest position before the reference (step 12), where a ΔY motion is again taken (step 13).   The motion continues over the entire area indicated by the Mask size until a point is reached where the next y-motion would cause Y to exceed Y_D (step 40).   At this point the table is commanded back to the Reference Position and the INDEX Cycle is terminated.

During the INDEX Cycle depressing the REPAIR switch causes the REPAIR Display count to be incremented by one.   Depressing the NONREPAIR switch causes the NONREPAIR Display count to be incremented by one.   The Table Translation Control can be used to bring the table to the desired location at any time.

Depressing the REVERSE switch causes the table to step in the reverse direction thru the pattern in Figure 3-2.   Reverse motion will continue unless the table reaches the start position (X_s, Y_s) at which point the REVERSE switch is inhibited.

Note that Y motion is not operable on the SAW Laser Repair System.

40
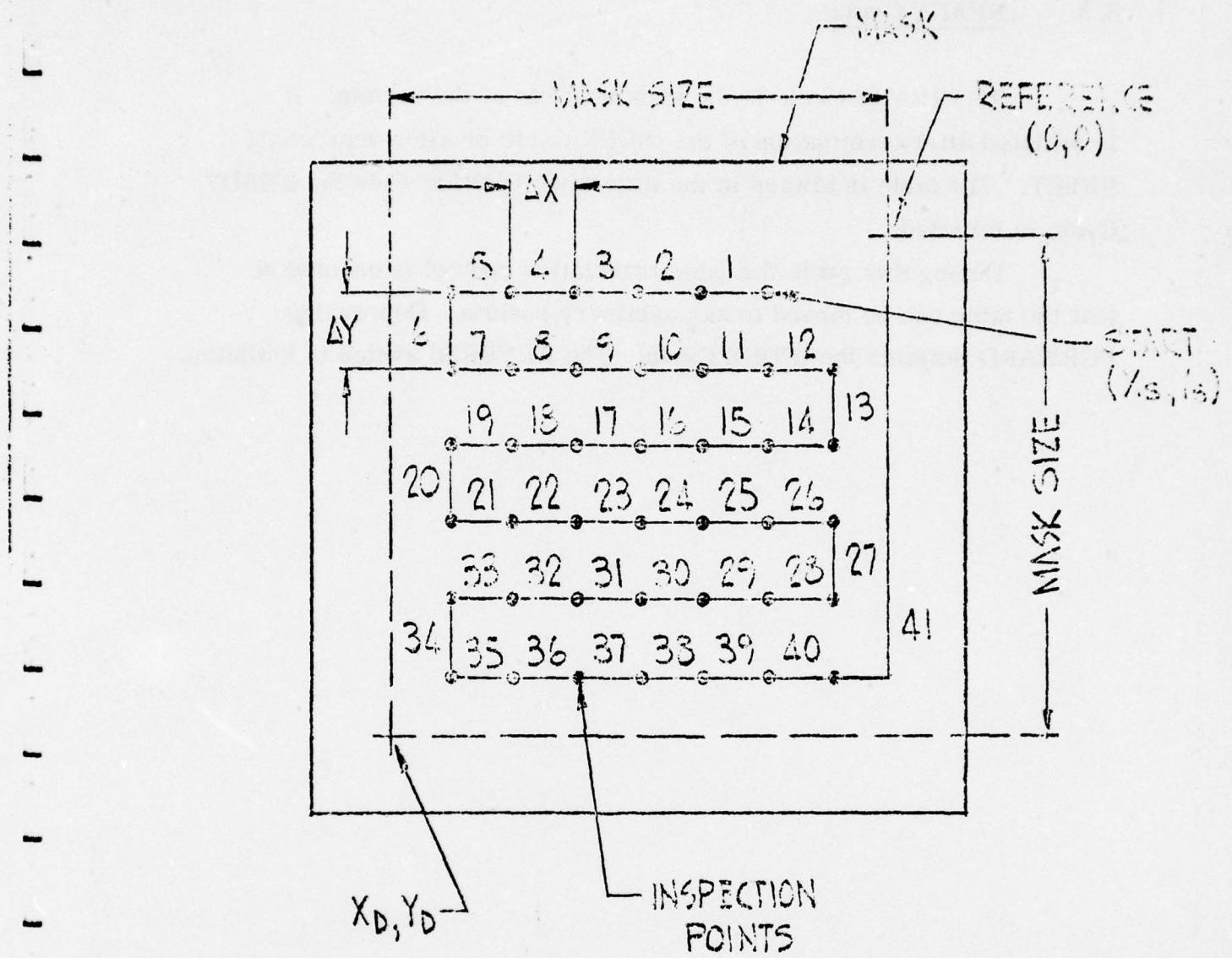
Figure 3. 2:   Motion Sequence in Index Cycle

3.3   READY Cycle

The READY Cycle is the standby cycle of the system.   It is initiated after termination of the INDEX Cycle or after depressing RESET.   The table is always in the Reference Position when the READY Cycle is initiated.

During this cycle the table translation control is enabled so that the table can be moved to any arbitrary position.   Depressing FORWARD initiates the INDEX Cycle.   The REVERSE switch is inhibited.

TABLE 3.1

SUMMARY OF CONTROL STATUS IN VARIOUS SYSTEM CYCLES

	CYCLE	
Initiate Conditions	INDEX Forward	READY Reset
Control		
Forward	Enabled	→ INDEX cycle
Reverse	Enabled	Inhibited
Repair/Display	Enabled	Enabled
Nonrepair/Display	Enabled	Enabled
		→
Mask Size	Enabled	N.A.
X-Index Digi	Enabled	N.A.
Y-Index Digi	Enabled	N.A.

The following is not present in the SAW Laser Repair System:

The SCAN (X & Y), JOG (X & Y), and RESET functions are enabled in all cycles.

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4.0   THEORY AND TECHNIQUES

4.1   Introduction

This section of the Model 801 Mask Inspection
and Repair Tool Operation Manual provides additional background
information about the laser and about the repair process, including
guidelines for system adjustment illustrated by typical examples.
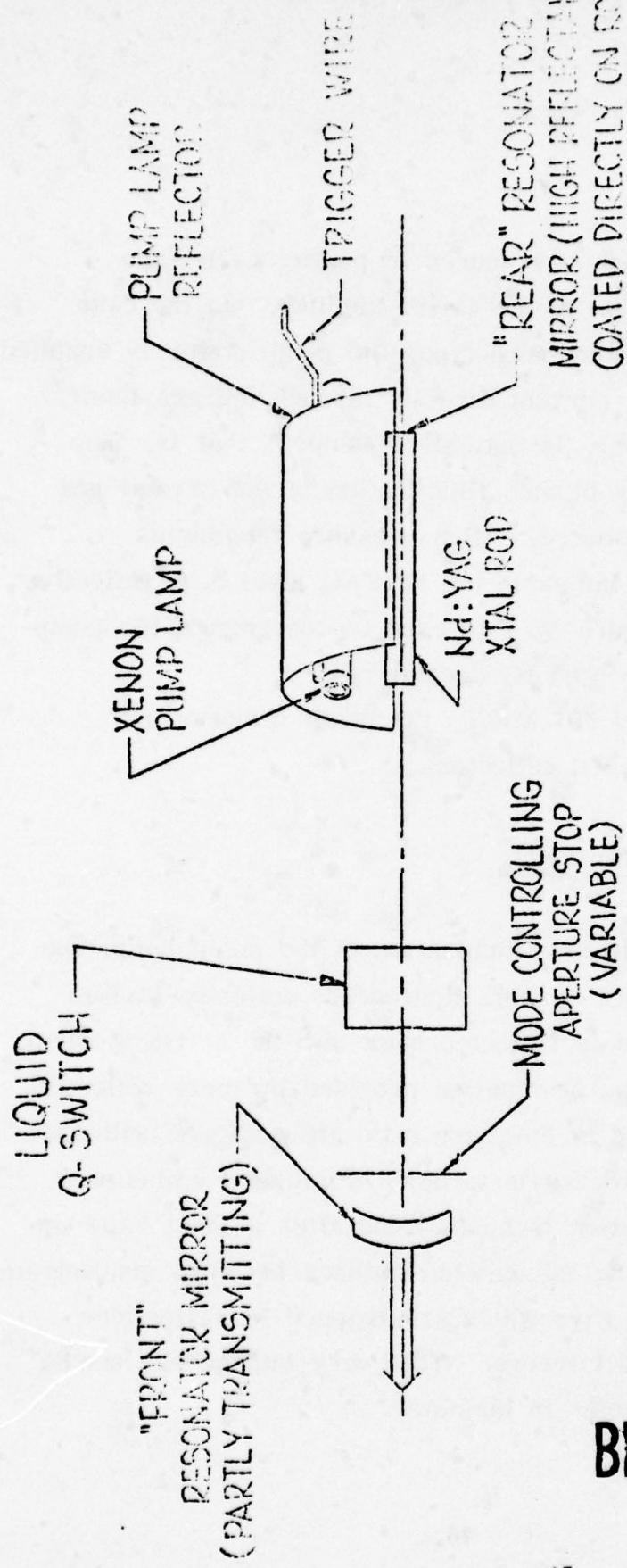
4.2   The Laser

Because of its unique properties with respect to
emission wavelength, output power capability and operational
characteristics, the Nd:YAG laser is well suited for the mask and
thin film machining required in repair. A basic understanding of the
laser's salient features and characteristics is helpful in obtaining
maximum performance.

4.3   Basic Construction

The designation, Nd:YAG, comes from the fact that
the active element of this laser is in the form of a thin rod (1/8 inch
dia. x 2-1/2" length) of synthetic gem crystal Yttrium-Aluminum-Garnet.
In the crystal, approximately 1% of the yttrium ions have been
substitutionally replaced by neodymium ions, and they are responsible
for the laser emission at the near infra-red wavelengths, $1.06 \mu m$.

The basic structure consists of an active medium (in
this case, the Nd:YAG crystal rod) located axially between two
accurately aligned resonator mirrors (Figure 4-1).   Since the rear
mirror is coated directly on the rod, only the front mirror need be
adjusted to provide this accurate alignment.

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PUMP LAMP
REFLECTOR

TRIGGER WIRE

"REAR" RESONATOR
MIRROR (HIGH REFLECTANCE
COATED DIRECTLY ON ROD)

Nd:YAG
XTAL ROD

XENON
PUMP LAMP

MODE CONTROLLING
APERTURE STOP
(VARIABLE)

LIQUID
Q-SWITCH

"FRONT"
RESONATOR MIRROR
(PARTLY TRANSMITTING)

FIGURE 4.1 – Nd:YAG LASER
MAIN ELEMENTS OF MODEL 8C1 MIRT
LASER UNIT SHOWN SCHEMATICALLY

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4.4   Excitation

Also provided is a source of power, called the
"pump", supplying excitation to the active medium.   In the case
of a gas laser like the helium-neon type, the pump power is supplied
by an electrical discharge current directly through the gas itself.
The Nd:YAG laser, however, is optically "pumped" that is, the
pump power is supplied by intense illumination of the crystal rod
from an "ordinary" light source.   High pressure flashlamps
are commonly used pump lamps in the Nd:YAG laser.   A reflective
system, illustrated in Figure 4-1, is used to concentrate the pump
lamp illumination onto the Nd:YAG crystal rod.

In the Model 801 MIRT, the pump radiation is
concentrated by gold-surfaced reflectors.

4.5   Stimulated Emission

Under the strong illumination of the pump lamp, the
Nd ions fluorescence.   Part of their flourescent emission strikes
the resonator mirrors and is reflected back into the active medium.
The Nd ions respond to the stimulation provided by these reflected
rays by an increasing rate of emission accurately aligned with the
reflected waves.   This process is termed "stimulated emission."

When excitation is applied and after a brief build-up
period, substantially all the Nd ion fluorescence becomes concentrated
into the narrow thread of rays which are trapped by reflections
between the resonator end mirrors.   This very intense ray bundle
is typically only a millimeter in diameter.

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To extract useful power from the laser, one of the resonator end-mirrors is partially transmitting to permit a small fraction of the internal beam to emerge.

4.6　Modes

Fixing the resonator end-mirror dimensions, curvature and separation determine a certain restricted set of internal ray patterns which can be trapped by the mirrors and which, therefore, can grow by feeding on the Nd ion fluorescence. This set of patterns is called the "modes" of the laser resonator. The basic or fundamental pattern is that one which comprises a single bundle of rays traveling exactly along the axis of the resonator, back and forth between the mirrors. It is termed the "fundamental" or TEM_{00}* mode and is characterized by a smooth transverse intensity profile with a maximum at its center, tapering monotonically at off-axis points.

Higher-order resonator modes represent rays traveling in a criss-cross fashion within the resonator at slight angles to the axis. They do not have monotonically decreasing transverse intensity profiles but are characterized by a number of peaks at off-axis positions in their cross-section. In general, these higher mode beams have larger total diameters and more total power. But in spite of the greater power, the ratio of total power to transverse cross-section area, that is, the power density may be less for these higher order modes.

Of importance with the Nd:YAG laser, and other laser types as well, is the fact that they always tend to operate in the highest order mode for which the internal resonator rays are efficiently trapped. A variable diameter aperture stop placed within

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*TEM for Transverse Electromagnetic Mode. The subscripts refer to the intensity profile of the beam wave front.

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the resonator, can therefore serve to control the mode order. If the stop is carefully adjusted to just permit the passage of rays associated with the fundamental TEM_{00} mode, the higher order, larger diameter modes will be "choked off". As the aperture stop is gradually opened, the laser will snap into successively higher order modes in a well-determined sequence. Figure 4-3 depicts this sequence for the first few modes. Since the sequence is always the same, it is convenient to label these modes as M-1, M-2, M-3, etc. as shown.

4.7   Second Harmonic Generation

The laser beam is directed through a non-linear crystal aligned to provide phase matching for both 1.06μm and 0.53μm radiation. The large 1.06μm fields induce a polarization in the non-linear crystal at the second harmonic frequency causing it to reradiate at a wavelength of 0.53μm. Optimum conversion is achieved by the phase matching condition.

4.8   Focusing

The Nd:YAG laser radiation may be brought to a focus by means of conventional glass optics. For a TEM_{00} mode beam which overfills the final objective, thereby providing nearly uniform intensity across the lens aperture, the focal spot will have an intensity pattern with half power points at a diameter, s, approximately equal to 0.8λ/NA where λ is the laser wavelength and NA the numerical aperture of the objective lens. The 100X objective used in the MIRT has a NA of 0.9 resulting in the ability to achieve focused spots of less than 1 micrometer.

This minimum spot diameter occurs only in the focal plane. However, for a distance of s^2/λ the spot is nearly unchanged, resulting in a depth-of-field of about 1 micrometer.

MODE ORDER [1]	MODE [2]	PATTERN
1	TEM_{00}	
2	TEM_{01*}	
3	TEM_{10}	
3	TEM_{02}	
4	TEM_{11*}	
4	TEM_{03}	

(1)   The mode order M of the $TEM_{p,\ell}$ mode is given by

$$M = 2p + \ell + 1$$

(2)   A cylindrical coordinate system is employed here to describe the various transverse modes. The * indicates the coherent superposition of two Space-Orthogonal Modes.

Figure 4-3:   Laser Operating Mode Sequence

4.9   Environmental Sensitivity

The Q-switched Nd:YAG laser used in the
Model 801   is a simple and rugged component. However, its
performance does depend to some extent on operating conditions.
The principal effects on performance are produced by the following:

a.   Alignment - Careful initial alignment of the
resonator mirror, and mode selector position and aperture
is important. Once set, they do not normally require re-adjustment
unless the laser is disassembled.

b.   Cleanliness - Small accumulations of dust or
oil films on the resonator mirror, crystal rod end faces or on the
pump lamp reflectors will degrade performance. It is important
that the tubes and covers within the laser resonator, which are
provided to protect the optical surfaces, be in place when the laser
is operated. They provide adequate protection for the optical surfaces
in the normal mask manufacturing environment.

c.   Temperature - The Model 801 laser
responds to variations in the ambient temperature. Over the
allowed operating range of 65°F to 85°F, the laser beam power will
decrease at the rate of 1% for each Fahrenheit degree rise in
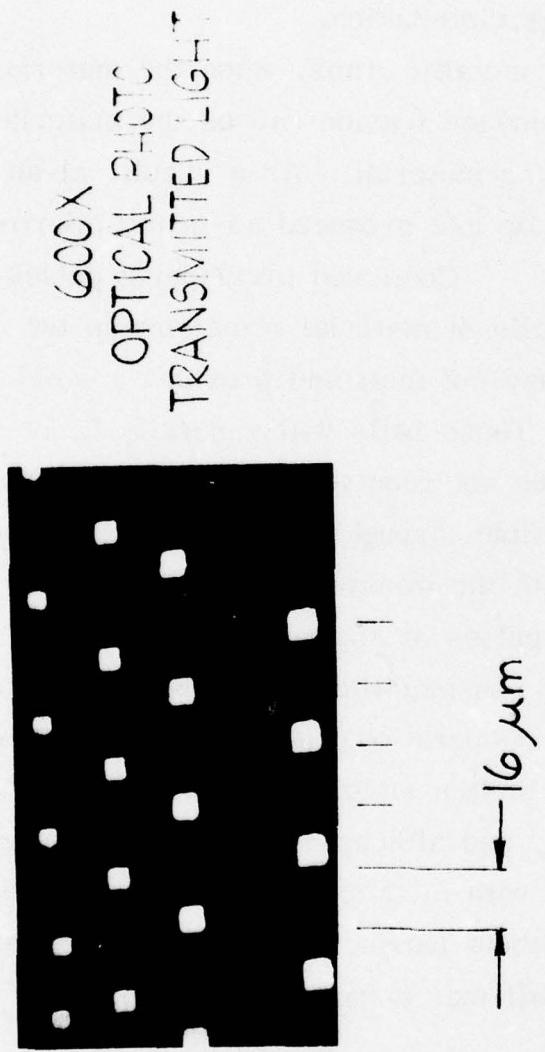temperature.

4.10   Mask Defect Repair

Defect repair is accomplished by melting or evaporation
of excess opaque material on the mask. In the case of metal films
(e.g. chromium) the process is usually melting, while in the case of
non-metallic films (e.g. iron oxide) the process is usually evaporation.

Absorption of laser radiation by the film material results in local heating. Since the film is extremely thin, it is essentially uniformly heated through its thickness. In addition, since the propogation time constant of the heat is long (typically several microseconds) compared with the pulse width (less than 0.5 microseconds), the transverse temperature distribution is directly related to the incident energy distribution.

In the case of metallic films, when the material reaches the melting point, surface tension causes the material to reticulate to the solid bounding material. As a result, clean holes with a slightly raised lip are produced as in the micro-photographs of Figure 4.4. Continued overlapping pulses will eventually result in small balls of material remaining in the cleared area since the thicker lip may not melt and provides a solid point for material accumulation. These balls will generally be of sub-micrometer size and are thus not resolved in subsequent mask use even though they are visible through a high power microscope Best results are obtained with the minimum overlap of pulses (preferably no more than 3 pulses at any point).

In the case of non-metallic films, the temperature rise is sufficiently fast that evaporation probably occurs before any material flow occurs in the molten state. The excess material is then removed as a vapor, and although the edge of the cleared region is not as uniform as with metals, it is possibly to remove large extents of material without leaving any residue. The amount of vapor produced is so small that it has no effect on either the mask or optics.

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600 x
OPTICAL PHOTO
TRANSMITTED LIGHT

Cr ON GLASS

16 µm

Figure 4.4a: Results of Thin-Film Machining

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600X
OPTICAL PHOTO
TRANSMITTED LIGHT

16 μm
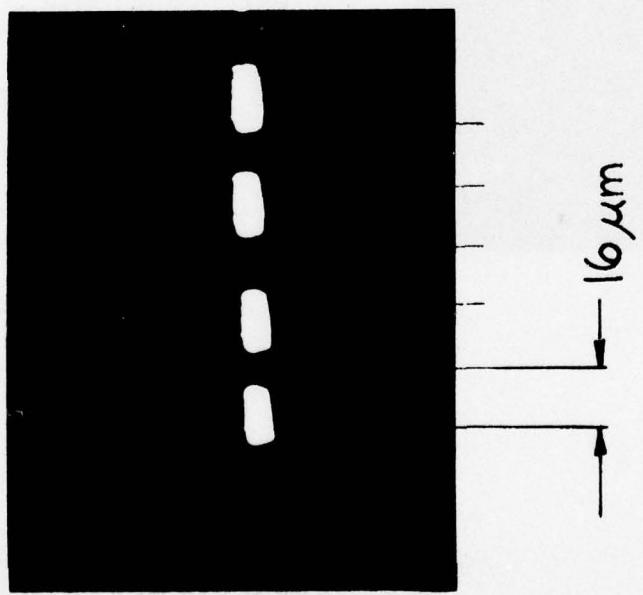
Cr ON GLASS

Figure 4.4b: Results of Thin-Film Machining
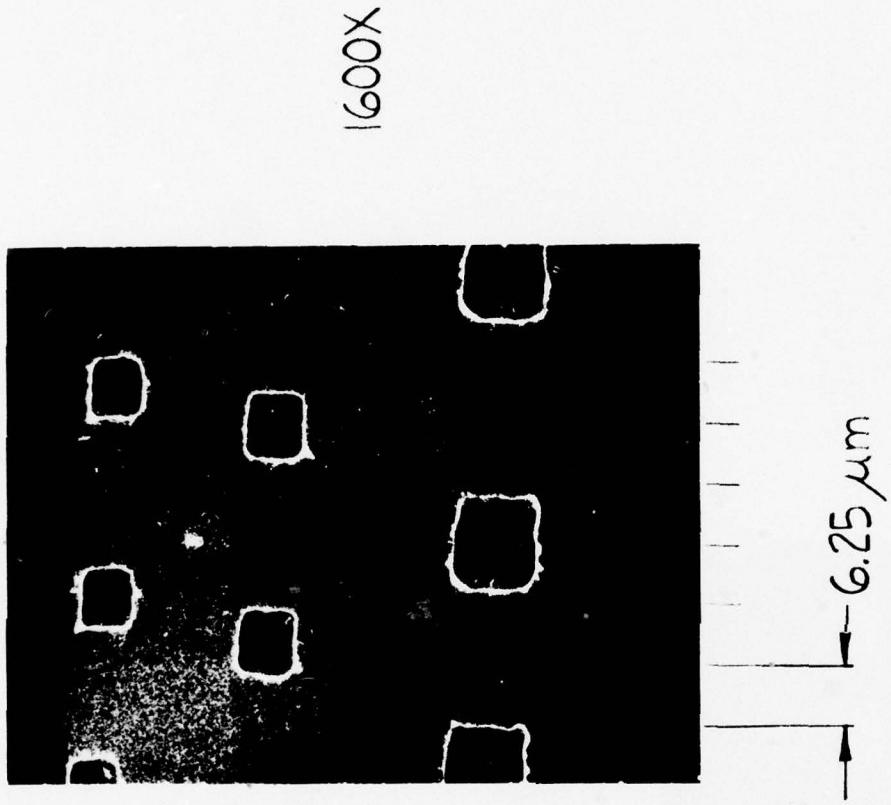
53

1600X

Cr ON GLASS-SEM PHOTO

6.25 μm

Figure 4.4c: Results of Thin-Film Machining
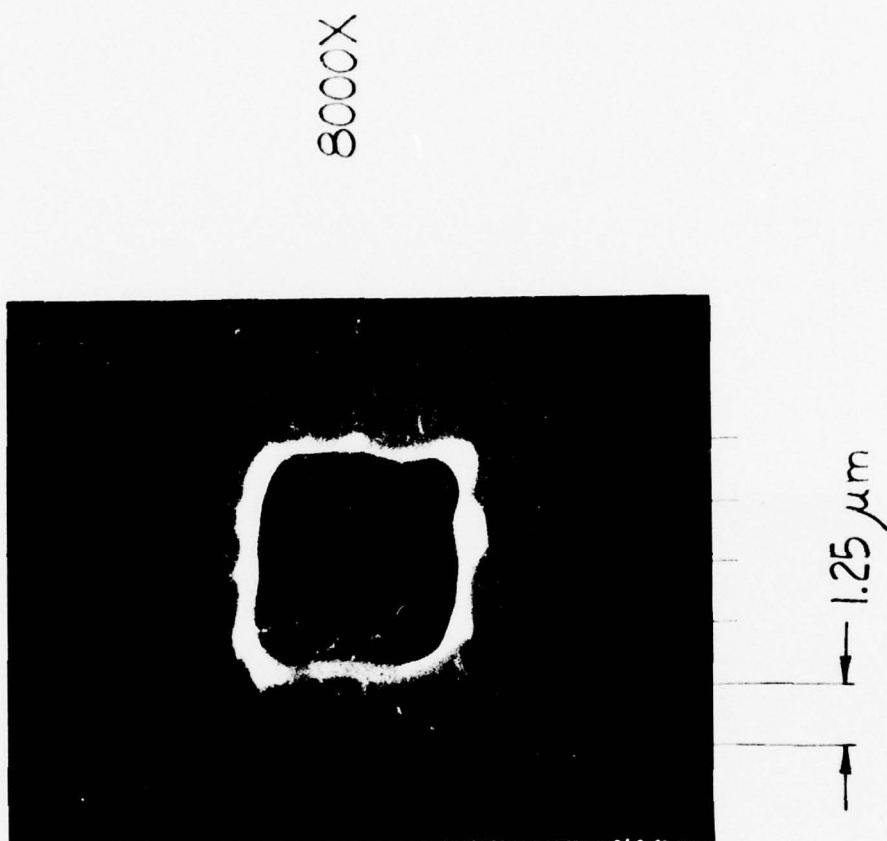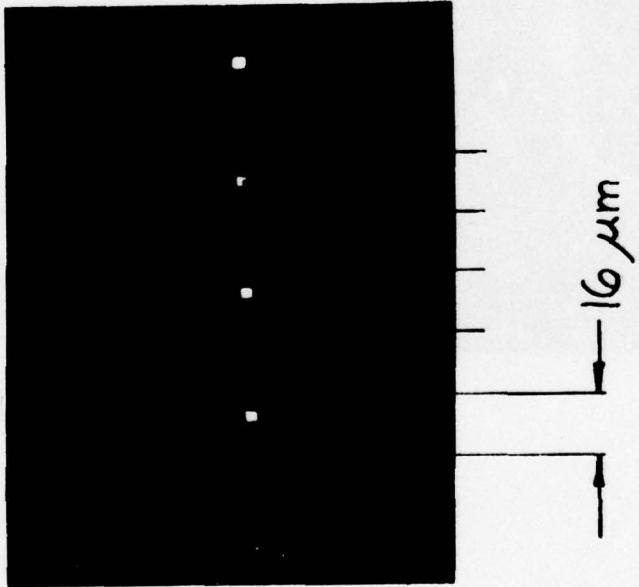
54

8000X

Cr ON GLASS – SEM PHOTO

1.25 μm

Figure 4.4d: Results of Thin-Filming Machining

55

600X
OPTICAL PHOTO
TRANSMITTED LIGHT

16 μm

IRON OXIDE ON GLASS

Figure 4.4e: Results of Thin-Film Machining

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8000X

1.25 μm

IRON OXIDE ON GLASS–SEM PHOTO

Figure 4.4f: Results of Thin-Film Machining

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600X

AFTER REPAIR

600X

BEFORE REPAIR

150X
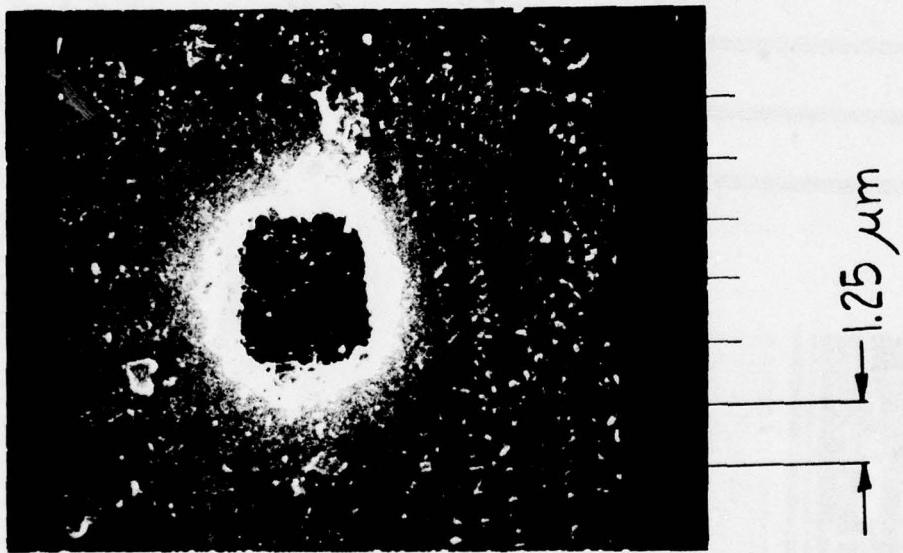
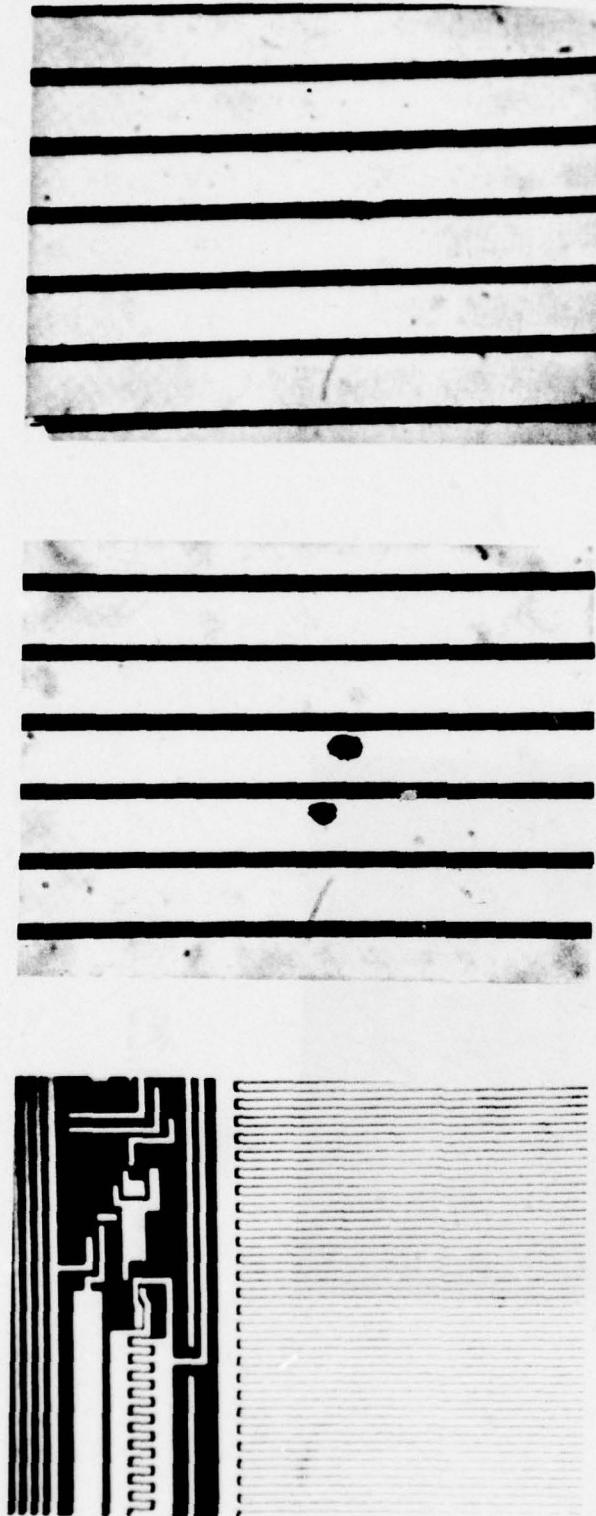CHROMIUM ON GLASS PHOTOMASK

Figure 4.4g: Results of Thin-Film Machining

## 4.11   Suggested Mask Repair Techniques

In light of the previous discussion, it is apparent that the following technique should be employed.

      a.   Always use the largest possible laser spot for a given defect to minimize the number of pulses required.

      b.   In the case of metal films, remove excess material by starting at the boundary between the excess material and a transparent region and working towards the correct edge as in Figure 4.5 .

      c.   Overlap pulses by the minimum practical amount.

      d.   Use the minimum energy level consistent with clean material removal to minimize the possibility of substrate damage.

Note that in the case of isolated defects in metallic masks, some residual balls of material will always occur and that the optimum condition is to produce a fine array of very small particles to minimize the possibility of resolving them during mask exposure.

TRANSPARANT REGION

CORRECT EDGE

2ND PULSE

1ST PULSE

3RD PULSE
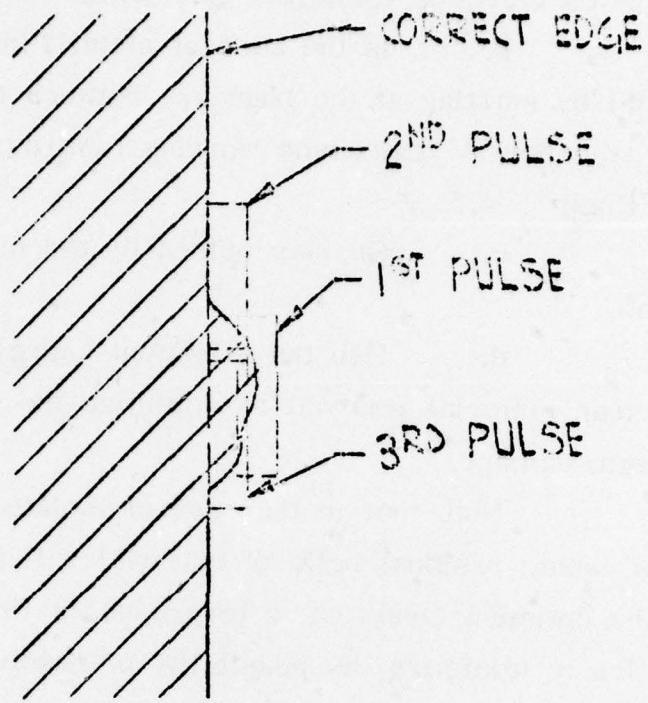
FIGURE 4.5 TECHNIQUE FOR DEFECT REMOVAL.

5.0   SYSTEM COMPONENTS

This section presents a general familiarization with the major units of the Model 801 and Model 811.   Refer to Figures 5.1 and 5.2 to assist in these identifications.

5.1   Card Rack

The Card Rack contains space for four P.C. cards which includes the microcomputer and table drive logic.   It is located in the right rear corner of the Model 801 as identified in Figure 5.2. The cards are as follows.

The Processor Card contains the basic microcomputer circuits. The microcomputer is based on the 4-bit Intel 4040 CPU and 4289 interface.   A 1702A PROM and a 4900 ROM provide the system program while four 4002 RAM's provide for data handling.   Note that two extra PROM sockets are provided on this board for special programs.

The Motor Driver Card contains logic and drive electronics to provide the proper sequence of pulses to the four-phase stepper motors on the table.   The card also provides a trigger pulse to the System Power Supply to increase the drive current from the 1/8 amp holding current per phase to the 1.5 amps drive current during table motion.   Identical circuits are provided for the X and Y axes.

Two additional slots are provided in the card rack for auxilliary and test cards when required.

CARD RACK

LASER POWER SUPPLY

LASER HEAD

VARIABLE ILLUMINATOR

DICHROIC DEFLECTOR

APERTURE ILLUMINATOR

APERTURE

UPPER ILLUMINATOR

SYSTEM POWER SUPPLY
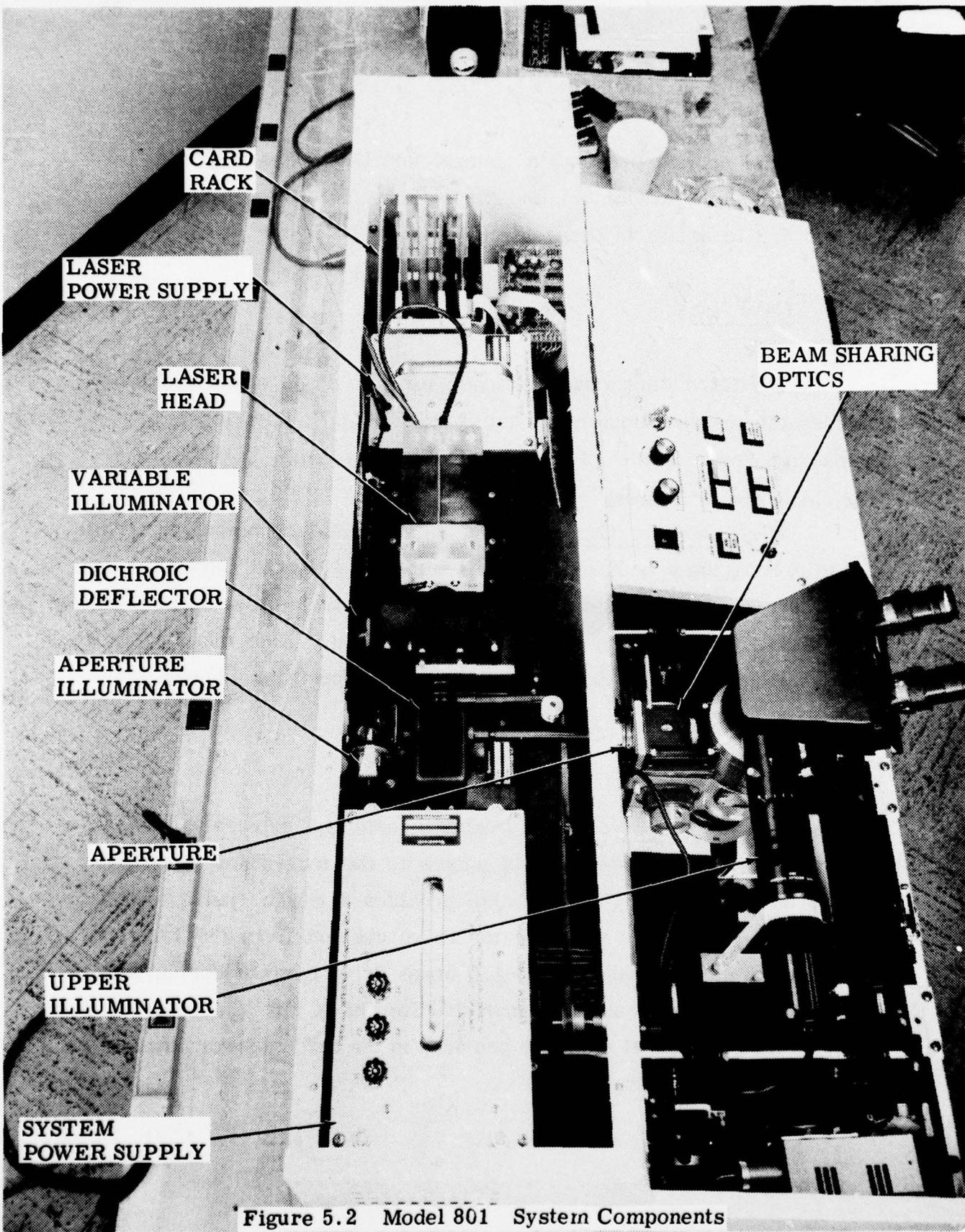
BEAM SHARING OPTICS

Figure 5.2   Model 801   System Components

5.2   System Power Supply

The System Power Supply is located in the left rear portion of the Electronics Unit and provides the following power sources.

The low voltage supply is a 3 section switching regulator supply to provide (1) +5 volts DC at up to 3 amps, (2) +12 volts DC at up to 1 1/2 amps and (3) -12 volts DC at up to 1 1/2 amps. Each stage is fused for short-circuit and over-voltage protection.

The 30 volt supply contains two current regulated DC sources of up to 3 amps each for driving the X and Y stepper motors. The output current can be switched from 1/4 amp to 3 amps via a signal from the Motor Driver Board.

The illuminator supply is an SCR controlled AC supply which provides voltage to the microscope illuminator lamp. Half of the full wave rectified supply is controlled by an SCR, to provide power to the illuminator. When fully lighted, the illuminator thus operates with half-wave rectified current at 12 volts peak (6 volts RMS) and 5 amps peak (2.5 amps RMS to provide 15 watts lamp power.

The AC distribution circuit contains a main power fuse, F1 (6 amp), to provide protection for the entire system at the AC input. Fuse F2, (2 amp) protects the 30 volt motor power supply. Fuse F3 (2 amp) protects the illuminator power supply, the +5 volts, +12 volts, -12 volt lines, and the System Power Supply cooling fan.

5.3   Laser Power Supply (Model 801)

The Laser Power Supply provides the trigger and discharge current for operation of the laser flashlamp. The unit consists of an

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SCR controlled charging supply, driven by a 3 KHz oscillator for
SCR turn-on and transistor triggered for turn off to permit 2%
voltage regulation. A 4μfd capacitor can be charged up to 1400 volts
in 150 milliseconds permitting operation up to 6 pulses/second.

The trigger source is provided by dumping a 0.5μfd capacitor
charged to 200 volts via an SCR. The pulse is stepped up by a 60:1
trigger transformer to 12 KV for lamp ignition. The SCR is triggered
by a 555 oscillator running at a rate set by a front-mounted potentiometer.
In the single pulse mode the SCR is triggered by the foot-switch,
dumping a capacitor. In both cases triggering is inhibited when the foot switch
is open.

The repetition rate is selected by a potentiometer mounted
on the front left hand side of the cabinet.

5.4   Laser Unit (Model 801)

The Laser Unit is composed of a conduction cooled pulsed
Nd: YAG Laser, external SHG, variable attenuator and dichroic reflector.
These components are all mounted on a base located by 3 pins which is
easily removed and reinstalled for servicing or replacement.

The laser head contains a 3 mm dia by 63 mm long Nd:YAG
rod mounted in a copper saddle for conductive cooling. The rod is
placed at one focus of a gold coated elliptical pump enclosure. An EG&G
FX 147C/flashlamp is located at the conjugate focus. The rear end of the
rod is coated for high reflectivity and forms one mirror of the resonator.
An external mirror mount contains a partially transmitting output mirror
to complete the resonator. The output mirror can be tilted in 2-axes for
resonator alignment. A Model 305 Mode Selector is also mounted within
the resonator for optimization of the laser TEM-00 mode output.

A saturable absorber Q-switch is located in the resonator to provide a single laser pulse of extremely short duration (about 50 nanoseconds) for most efficient thin film machining.

A SHG assembly is located external to the resonator and comprises a lithium iodate (nonlinear) crystal hermetically sealed in an adjustable mount. The mount permits X-Y motion for selection of the optimum optical path through the crystal and tilting for phase match adjustment.

The Variable Attenuator comprises a glass plate coated with an increasing thickness of nichrome along its length so that the optical density varies from 0 to 3.5 along the length. The plate is driven by a rack and pinion connected to an external control knob located next to the repetition rate control.

The dichroic mirror serves to deflect the laser beam into the system optical path.

5.5 Laser Optical Train (Model 801)

The Model 801 optical system is designed to provide optimally focused spots for machining of thin film devices. These spots are obtained by expanding the $0.53\mu m$ radiation with a collimating telescope and overfilling the 100X objective to assure utilization of the full f-number.

Coincidence between the focal points of the SHG radiation and visual microscope image is achieved by X-Y adjustment of the negative lens in the telescope and by axial motion of the negative lens for focusing; focusing is accomplished via a thumbwheel on the assembly. (Figure 4.5) (The aperture size levers shown in Figure 4.5 have been deleted in this system).

5.6 Microscope

The basic microscope components are manufactured by Leitz and comprise a binocular with 12.5 x wide field eyepieces, a vertical illuminator

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with tube lens for infinity-corrected operation and a quad-objective nose piece with two standard objectives (100X, 10X).

In the Model 801 inspection and repair station (Figure 5.4). The binocular and vertical illuminator are mounted on an A-O series 3000 focusing barrel with a quad-objective nosepiece. The Leitz objectives (100X, 10X) are mounted in the A-O nosepiece and focusing is accomplished by motion of the objectives only. This A-O section also contains a dichroic mirror to couple the laser radiation into the microscope and the fine motion optics.

The right-hand eyepiece of the microscope contains a special reticle as shown in Figure 5.5. The circles indicate a 3 mil diameter with the appropriate objective. Within this field, a defect can be positioned by means of the fine motion control for repair. The field-of-view with each objective is given in Table 5.1.
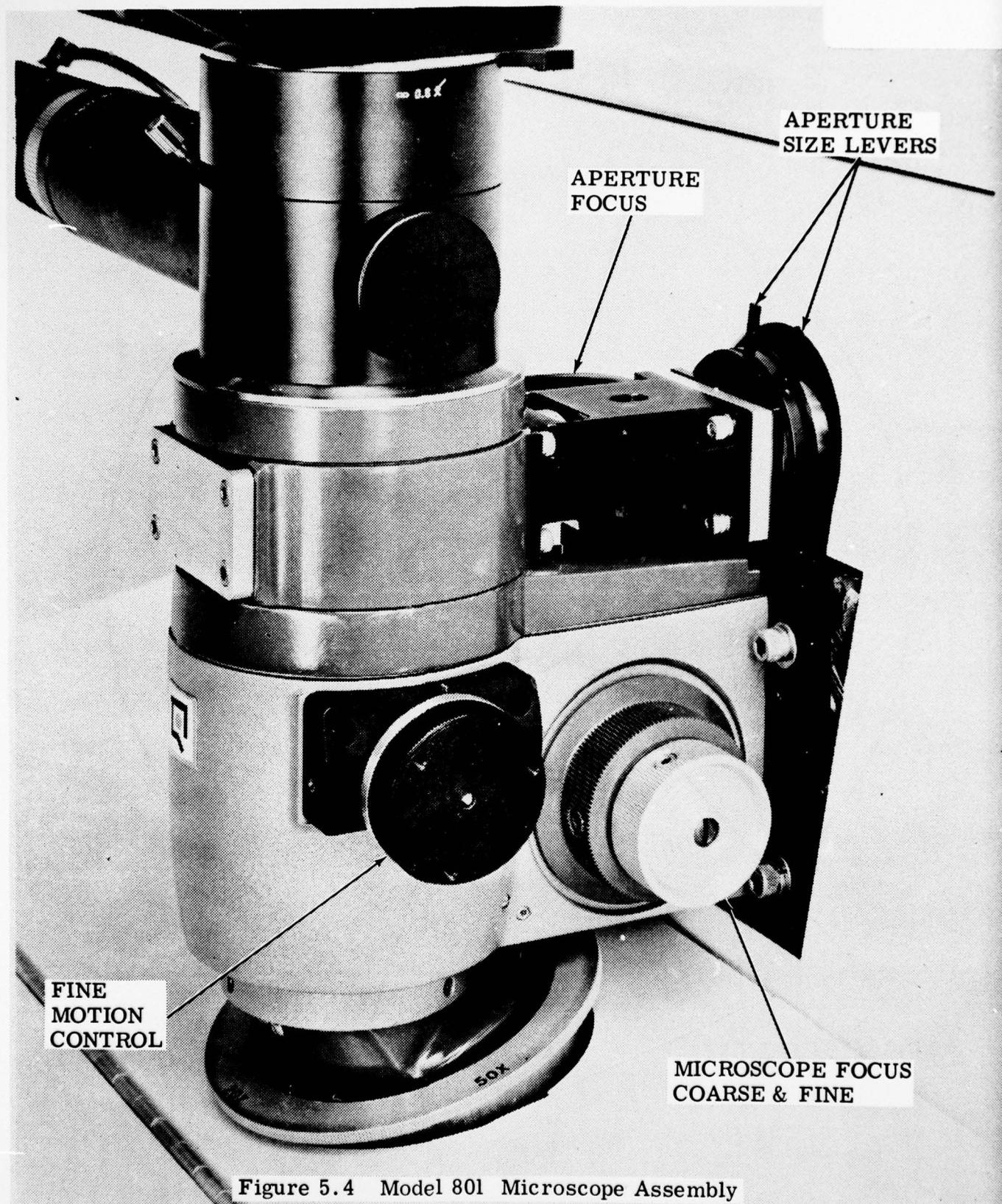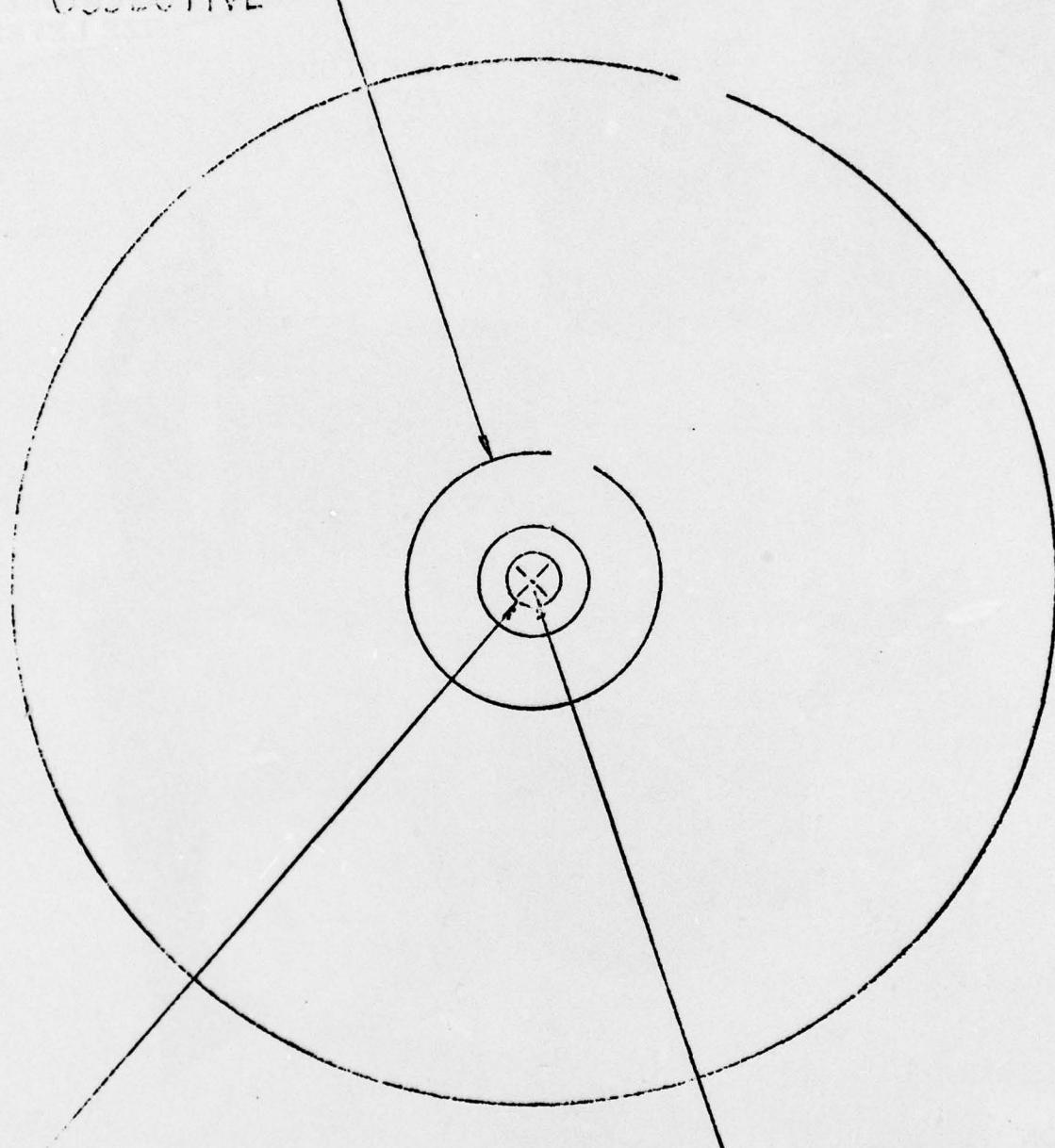
APERTURE
SIZE LEVERS

APERTURE
FOCUS

FINE
MOTION
CONTROL

MICROSCOPE FOCUS
COARSE & FINE

Figure 5.4   Model 801 Microscope Assembly

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TARGET FIELD
FOR 100X
OBJECTIVE

POSITION OF LASER
SPOT

TARGET FIELD
FOR 10X
OBJECTIVE

FIGURE 5.5 RETICLE PATTERNS

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TABLE 5.1

FIELD OF VIEW

OBJECTIVE	MODEL 801
10X	70 mils
100X	7 mils

5.7 Fine Motion Optics (Model 801)

The Model 801 employs a unique optical system to provide fine motion control of the beam for repair operation. The system provides motion over a range of ± 15 micrometers in X and Y with a resolution of better than 0.5μ at mag. of 1000X. Motion is provided by a single knob control on the side of the A-O focusing barrel. Vertical motion of the control produces X-axis motion of the beam; rotation of the control produces Y-axis motion of the beam. The two motions are accomplished by independent rotations of a two-axis gymbal with sufficient friction to permit X-only or Y-only motion.

5.8 X-Y Table

The table (Figure 5.6) provides X-Y motion via two rod-supported stages. Each stage is driven by a stepper motor and a .2 inch lead screw providing 1 mil steps. The accuracy is ± 1 mil with ± 1 mil backlash. Orthogonality is ± 1 milliradian. Total travel is 5 inches in each axis. X and Y reference position sensors locate the Reference Position to ± 1 mil.

The Y stage carries the mask slide plate for loading and unloading of the mask. Mask positioning is provided by 3 pins and a magnetic holding strip that manually loads the mask against the pins.

Slide plates are available for any size mask with the appropriate clear viewing area.

5.9 Safety Enclosures

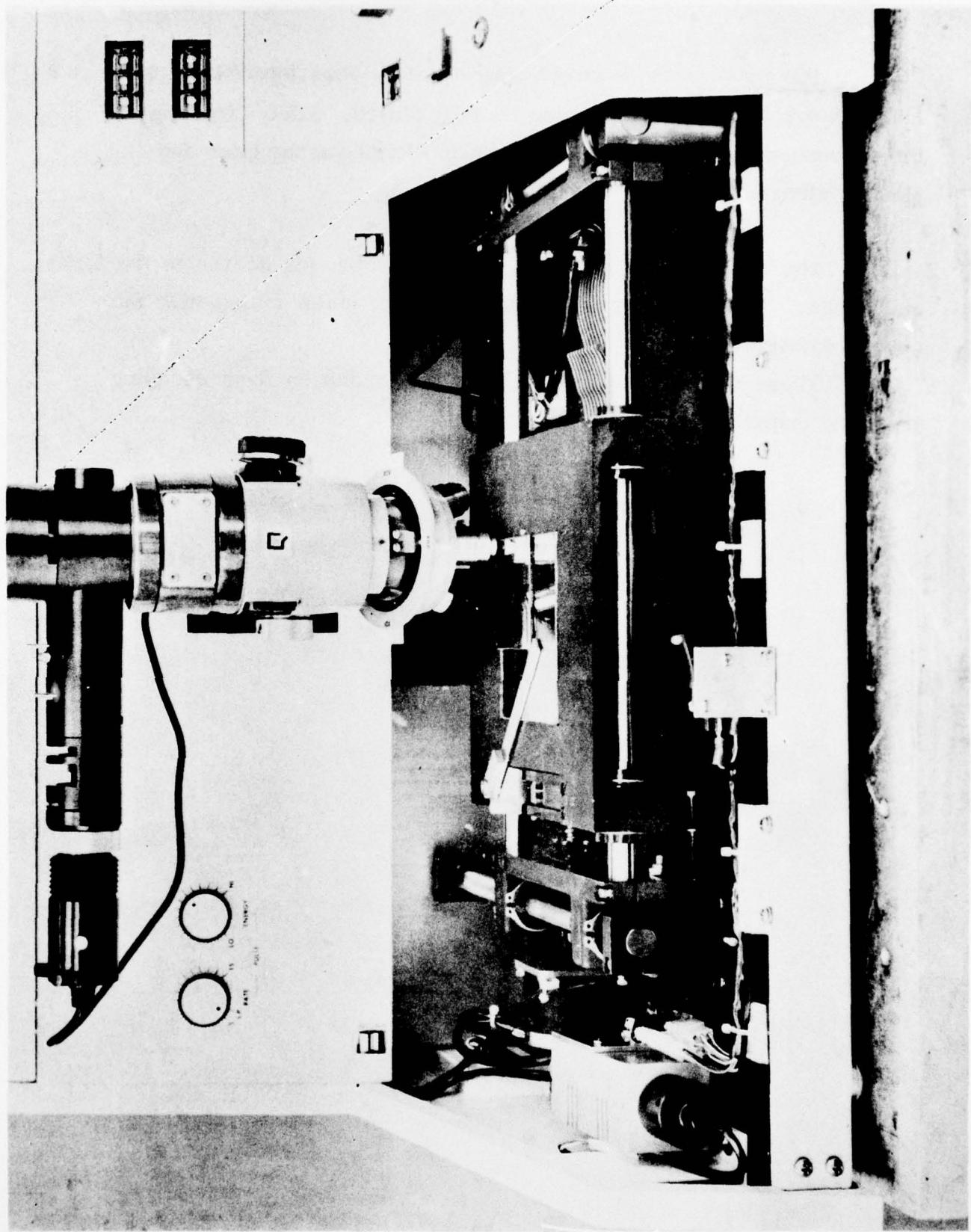The Model 801 MIRT (Figure 1.2) is totally enclosed in a protective housing.

Figure 5.6: MIRT X-Y Table

The mask area is covered by a safety door interlocked to inhibit laser action **unless the** door is fully closed. Safety filters in the microscope provides in excess of 100db filtering at the laser and SHG wavelength.

The top cover of the cabinet is removable for access to the laser and optics.   This cover is also interlocked to inhibit lasing with the cover removed.

These safety features, prevents any radiation from escaping from the enclosure or microscope.

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